DOCUMENT RESUME

ED 051 650 EM 009 001

AUTHOR	Matheny, W. G.; And Others
TITLE	An Investigation of Visual, Aural, Motion and Control Movement Cues.
INSTITUTION	Life Sciences, Inc., Fort Worth, Tex.
SPONS AGENCY	Naval Training Device Center, Orlando, Fla.
REPORT NO	TR-69-C-0304-1
PUB DATE	Apr 71
NOTE	109p.; 27 June 1969 - 27 June 1970
EDRS PRICE	EDRS Price MF-$0.65 HC-$6.58
DESCRIPTORS	Aural Stimuli, *Conceptual Schemes, *Cues, *Flight Training, Kinesthetic Perception, Military Training, *Multisensory Learning, Psychomotor Skills, *Simulators, Visual Perception, Visual Stimuli

ABSTRACT

A study was conducted to determine the ways in which multi-sensory cues can be simulated and effectively used in the training of pilots. Two analytical bases, one called the stimulus environment approach and the other an information array approach, are developed along with a cue taxonomy. Cues are postulated on the basis of information gained from the outside visual world, from sounds generated by the aircraft, and from aircraft motion and control movements. The physical characteristics of the postulated cues are emphasized. Hypotheses are developed based upon the effects of the postulated cues as they function independently and as they function in interaction with cues in other modalities. Experimentation is recommended which will lead to the verification and/or the modification of cue postulations. (Author/JY)

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Technical Report: NAVTRADEVCEN 69-C-0304-1

AN INVESTIGATION OF VISUAL, AURAL, MOTION AND CONTROL MOVEMENT CUES

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Life Sciences, Inc.
Fort Worth, Texas
Contract N61339-69-C-0304
NAVTRADEVCEN Task No. 8273

April 1971

DoD Distribution Statement

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NAVAL TRAINING DEVICE CENTER

ORLANDO, FLORIDA

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EM009001

NAVTRADEVCEN-69-C-0304-1

AN INVESTIGATION OF VISUAL, AURAL, MOTION AND CONTROL MOVEMENT CUES

ABSTRACT

This report is devoted to the determination of how multi-sensory cues can be simulated and effectively used in the training of pilots. An analytical basis and cue taxonomy is developed and cues are postulated on the basis of information gained from the outside visual world, from sounds generated by the aircraft, and from cues resulting from aircraft motion and control movements. Description and measurement of the physical characteristics of the postulated cues are emphasized. Hypotheses are developed based upon the effects of postulated cues as they both function independently and interact with cues in other modalities. Experimentation is recommended which will lead to verification or modification of cue postulations.

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FOREWORD

The aircraft pilot maintains control of his vehicle and accomplishes his mission through the information obtained by his senses. It is easy to classify the sources of this sensory information. There is the outside visual world, the cockpit display, motion, vibration, control feel, sound and even smell. To the experienced pilot, these sensory inputs provide important cues which, when processed, lead him to appropriate control inputs, or to prompt remedial action.

The purpose of this project is to examine these sensory inputs, to classify them in meaningful categories, to assess their information content singly and in combination and to develop hypotheses testable on a simulator research vehicle.

The hoped-for end result of this research is a better understanding of the pilot's sensory environment leading to the incorporation of environmental simulation in flight training devices and the development of instructional strategies to bring novice pilots quickly up to speed in their use of sensory information.

Harold A. Voss

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Scientific Officer

ACKNOWLEDGEMENT

The authors wish to express their appreciation to Mr. H. A. Voss, our NTDC Project Monitor, who provided valuable guidance and technical assistance during all phases of the task.

We would also like to thank Joseph A. Puig, Leonard Ryan and Dr. James J. Regan of the Naval Training Device Center for reviewing the preliminary manuscript.

Thanks are due to Mr. M. A. B. Vianello for providing consultative services during the preliminary stages of the research.

Finally, we wish to thank Mrs. Betty Acton, Life Sciences, Inc., for her assistance in compiling and typing the manuscripts.

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1.0 INTRODUCTION

1.1 PURPOSE AND SCOPE

It is generally held that piloting is primarily a visual-psychomotor problem but that the pilot utilizes information from sounds and motion sources in the process of controlling his aircraft. The permutations in terms of cues available, as well as the multiplicative relationships that could (and perhaps do) exist have expanded the scope of the problem of multi-sensory cueing to the point that, in the past, it has been viewed as prohibitive as a subject for research. As a result much information has been compiled regarding some individual areas such as vision (e.g., Wulfeck, Weisz, & Raben, 1958), while much less information is available with respect to others such as audition. Further, even less information is available concerning the interactions of cues in the control of aircraft. At the same time the scope of the problem has not diminished. On the contrary, the variety of aircraft types and the variety of propulsion systems have served to complicate the problem and increase its scope.

The source and content of cues available to the pilot would seem, then, to be a function of the man, the machine, the medium, and the mission. (Bond, Bryan, Rigney & Warren, 1962) In listing these four areas or sources of cues one readily sees the ramifications. Yet a logical analysis of the problem has led to the conclusion that there are some things about cues that are constant and that would hold across these four areas. This has special meaning in the field of simulation. The individual differences in man, the proliferation of machines, the variety of extra-vehicular environmental factors (the media) and the various types of missions are indeed different in terms of stimuli and responses. Yet, there are some constants that hold over these variations. It becomes a task of postulating these constants, quantifying and specifying them in physical terms and applying them to the simulator, if the simulator is to become anything more than an instrumented procedural device. The magnitude of the problem is evident.

This report represents an attempt to deal directly with the problem of multi-sensory cueing, but the scope has been restricted. The purpose of this report is to:

1. Outline previous pertinent research efforts in this area.
2. Establish an appropriate analytic basis for postulating source and optimal content of cues in the total aircraft environment.

3. Suggest research in order to both test postulations and supplement areas in which information is marginal.

4. Make determinations regarding the suitability of NTDC simulation facilities for the conduct of recommended research.

In summary, even though the scope of the problem of multi-sensory cueing is quite large, this research effort has been based on the a priori assumption that there are constants within sensory modalities such that the problem need not deal with all combinations and permutations of man, machine, medium, and mission. Consequently, this effort has confined itself to postulations regarding the concept of the cue, its source and content, its detectability and utilizability, its need as a function of experience, and simulation fidelity as it relates to the needs of the pilot. Postulations have been based on published research, expert opinion and judgment, pilot reports, and in some cases the postulations await verification through controlled experimentation.

This report deals with cues from four sources: vision, audition, control movements and motion. Chapters deal with these modalities separately along the general considerations outlined above. In addition, a chapter has been devoted to interaction of these cues and recommendations have been made for further research as well as for research equipment requirements.

1.2 BACKGROUND

A review of the literature demonstrates the widespread use of the word "cue", but there is virtually no indication as to the meaning intended in every instance. It is to be supposed that all who read such literature will immediately understand the context and connotation of the word. But as reading progresses in the field of multi-sensory cueing it becomes apparent that a distinction must be made between such word-concepts as sensation, perception, information and cue insofar as the concept cue is concerned. This is because the word cue may be taken to mean any or all of the other words. Therefore, for purposes of this report, the word cue has been operationally defined as objectively identifiable information which has a purposive nature. It is information which is presented to a pilot-subject who must subjectively evaluate and attach some meaning to this information because it calls for some purposive action or decision on his part. It is, in this sense, goal-directed information.

This research was governed by the precept that any postulation, definition, or elaboration of a cue would have to be in terms that are capable of being specified physically and quantitatively for computer application to the simulator. Dealing with cues on a qualitative level was not ruled out, but only those cues that met the criteria outlined above were deemed acceptable.

1.3 A TAXONOMY OF CUES

Preliminary analysis of the problem led to a delineation of a variety of cues which functioned in a number of ways in the aircraft environment. In order to deal more effectively with this universe of cues, they were divided into sets and sub-sets, yielding a classification of cues based on their essential character and role in providing information to the pilot. This classification also aided in the determination of what information qualified as a cue and led to postulations regarding the character of the cues.

For any given event there are two disjoint sets of cues; relevant cues and non-relevant cues. Relevant cues comprise that set of cues which is directly useful to the control of the aircraft or to the pilot's making decisions as to the state of the aircraft or its control. These cues are essential to the operation of the machine and must be provided for effective control.

The set of relevant cues is comprised of subsets of primary, secondary, complementary, and conflicting cues. These subsets were based on the premise that the pilot has, for a given situation, an hierarchy of preferred cues in some specified order such that he seeks a primary cue from a set of primary cues available. If he obtains, for example, a primary visual cue, he may utilize another cue in the visual realm to reinforce his primary cue. This cue has been classified as a secondary cue. If on the other hand, the pilot obtains a cue from another modality to reinforce his primary cue, this second cue has been classified as a complementary cue. Thus, cues in the same modality that serve to reinforce primary cues were classified as secondary while those from a different modality which serve to reinforce the primary cue were classified as complementary.

Cues which the pilot uses for control of his aircraft may be received by two different sense modalities and these cues can be in opposition to each other in terms of the information they present. These conflicting cues are demonstrated in any of several ways. The pilot may experience vertigo and feel that his aircraft is departing from straight and level as a function of the cues received through his vestibular apparatus. At the same time his visual cues may tell him that he is maintaining his aircraft in the proper attitude. Here the motion and visual cues are in conflict.

The set of non-relevant cues were deemed to be non-essential to the successful operation of an aircraft. However, they do have application to the simulator problem. These cues serve to add realism or in some other way add to the face validity of the task.

There may be several primary cues acceptable to the operator, any of which may be chosen and reinforced by any one of a number of secondary or complementary cues. These cues are task-dependent and are subject to modifications with time and the circumstances or needs of the individual.

An implicit assumption was made that a cue, in order to be a cue, must be discriminable. There are times when information in the form of a cue is not discriminable by the pilot. In this situation certain information may mask the cue, serving to increase the threshold of detection. One may consider these effects as masking cues in the sense that they obscure the relevant cues. However, this may be something of a misnomer since they could qualify as opposing or conflicting cues in some instances. At any rate the problem was considered to be of sufficient importance to warrant separate consideration.

As indicated earlier a cue is a member of a given set only in a given circumstance. The characteristics of the cues were considered in order to demonstrate this.

One of the characteristics of cues considered in making the several postulations in this report was the transitive nature of the cues. As the nature of the machine, the medium, and the mission changes the needs of the man change. In conjunction with these changes a relevant cue may become non-relevant. Or a primary cue may become secondary, etc. In other words, cues are task-dependent and also depend on momentary needs of the operator; this is reflected in the characteristic ability of a cue to supplement or oppose other information, to function independently or to be dependent on other information, or to otherwise change in the hierarchy of the operator.

Cues were also considered to be relative in their state of permanence. That is, the horizon may serve as a relatively stable cue to the attitude of the aircraft whereas a momentary vibration detected by the whole body may be a transitory cue indicating a pocket of turbulence. This may be contrasted with a vibration which compounds itself and increases in magnitude to indicate that a system has failed.

Many of these characteristics may be subsumed under a general heading of cue interaction. This was indeed considered to be one of the central problems in multi-sensory cueing. (A separate chapter has been devoted to this problem.) Suffice it to say, at this point, that the problem of interaction is not unlike the concept of interaction in statistical terms and was considered to be such in this study. Thus, information which has the potential to act as a cue may behave, as it were, differently as the conditions vary under which this information is presented and detected. This may serve to explain, at least partially, why the same information can take on the properties of reinforcing, opposing, complementing, masking, etc.

An important consideration in postulating aircraft control cues was that the term control implied a desired condition or standard to which the system was being compared and controlled. This standard has been termed the referent. Control also implied a controllable index which the pilot sought to maintain in some position in relation to the referent. For example, in seeking to control the bank angle of his aircraft the operator seeks to maintain the wings, i.e., the control index, in some position relative to the horizon, i.e., the referent. Thus, it was important in postulating cues to control that the stimuli giving rise to both the referent and the controllable index be identified and described.

Another important consideration in the postulation of cues was that the aircraft is a dynamic system. While the position of a desired index relative to a fixed referent is important, the time derivative of position is equally so. Rates and accelerations were postulated to be referred to standards. Parenthetically, the standard may be "no rate" or "no acceleration" and the cue to control is comprised of the perception of the deviation from such a standard. Thus, information as to rates and accelerations and their relation to desired or referent rates and accelerations also provides cues for control in the system and points to the dynamic characteristic of cues.

To appreciate this dynamic aspect of the system in the postulation of cues one should consider the movement of the aircraft as a changing physical event in which positions are changed with attendant time variables -- rates, accelerations and rates of change of acceleration. To the extent that these physical events are perceptible to the operator they may provide cues to him for exercising control. The importance of considering the dynamic actions of the system lies in the fact that these varied physical events may be perceived differentially as cues by the several sense modalities. A given physical event, i.e., departure of the aircraft from level flight, might provide a cue through the motion senses as an acceleration or rate of onset of acceleration while the cue through the visual modality of a rate or a positional change might occur later in time. It is this differential sensing both with respect to the aspect of the physical event which serves as a cue and the time at which the cue is detected by the given sense modality which provides an additional clue to the understanding of the interaction among cues.

1.4 CUE UTILIZATION: SOME INTERACTIVE RELATIONSHIPS

In developing postulates about control cues it was helpful to develop an analytical approach and to apply it to the problem. The approach used here considers the aircraft pilot to function essentially as a process control device. As such his task is considered to be: 1) information or data acquisition, 2) information integration, and 3) information output through control movements or verbal communications.

Several contingencies arise when man interfaces with machine and these were considered to be related generally to the problem of interaction of cues. The category of the cue and the sense modality through which the cue is received are both dependent upon a number of factors in the man-machine control loop which change over time. As pointed out earlier, it was postulated that interactions may occur when cues from one sense modality mask or oppose those being perceived by another sense modality. The differential sensing of the aspects of the physical event can be illustrated by a comparison of the visual and motion senses. The differences in time of sensing the cue may be due to the fact that the two sense modalities are stimulated by different aspects of the physical event. Perhaps the visual sense responds to the cue of differences in position and time-rates of changes in position but is not particularly responsive to accelerations and rates of onset of acceleration. The motion senses on the other hand may be cued to the event through sensing accelerations and rates of onset.

Cues were postulated to vary as a function of the dynamics of the vehicle being controlled. That is, certain cues may be appropriate or not as a function of the stability of the vehicle. The time derivatives of aircraft movement occur in a sequence which, under most conditions of aircraft operation, make the cues time-dependent in the sense that the motion senses are stimulated first. Precise control of the aircraft is then "modality dependent" as a function of the aircraft dynamics. Cues may be present or absent, relevant or otherwise as a function of these dynamics. Highly stable and/or slow responding systems such as might be envisioned for space vehicles may provide virtually no cues to the motion sense. Control of such vehicles might be almost solely dependent upon visual cues. For control of a highly responsive system such as a military aircraft, however, great dependency may be placed upon motion cues for precision of control.

During normal aircraft flight, rotational movements about its axes were postulated to provide cues to the motion receptors before they cue the visual receptors. Motions of the aircraft along X and Y space axes are postulated to be more likely to cue first the visual sense through rates and differences in position rather than the motion senses because of the low accelerations and rates of onset usual to these systems. In order to provide useful data about the interaction between cues and vehicle dynamics, it is necessary to provide specific postulates as to how the cues are dependent upon specific parameters of dynamics such as frequency response and gain of the dimension of the vehicle being controlled and to test these postulates empirically.

An important interaction occurs between the characteristics of the visual display and the characteristics of the motion platform system. Such parameters of the visual display as gain and resolution may have a direct effect upon the importance of motion cues in control of the system.

An important interaction may occur also when the feedback characteristics of the controller which the pilot manipulates at a given time is considered. For example, the immediacy of feedback and the accurate positioning of the controller is postulated to be dependent upon controller characteristics. This dependency is particularly apparent when controls with and without centering are compared. Moreover, control stick mass, damping and friction will affect its reaction as inertial mass to simulator movement. Thus, the interaction of stick mass and quality of simulator motion are considered to be important in the differential effect they may have on pilot performance.

Another interactive effect or factor upon which cues are dependent is that of the task being performed by the pilot. When the pilot carries out a compensatory tracking task such as low altitude high speed flight, the motion cues may be postulated to precede the visual cues as indicators of change of aircraft attitude. This is to be contrasted with the task in which the pilot is pursuing a target at high altitude under non-turbulent conditions. Here the movement of the target in terms of its positional and rate change may provide cues to the visual sense but not to the motion senses.

The concept of an effective time constant (t_e) of the man-vehicle system was deemed helpful in understanding the interaction effects. The effective time constant notion is that precision of closed-loop control is a function of the rapidity with which the operator perceives the results of his control inputs into the system. The more rapidly he receives feedback the more precise can be his control up to a point, after which too rapid feedback can disrupt control. The relationship between the value of t_e and precision of control is postulated to be a hyberbolic function. The rapidity of feedback is a function of the dynamics of the system being controlled and of characteristics of the operator - most particularly his threshold for perception of the vehicle output. The time between control input initiation and perception of vehicle output is termed the effective time constant (t_e) of the system.

An important point in the concept of t_e is that different sense modalities may have different thresholds for a given vehicle movement and therefore different time constants. It is also apparent that it may be possible to manipulate the stimuli to the different sense modalities differentially so that their respective effective time constants may be varied.

In a simulator which has no motion at all the motion sensors are not stimulated so human operator response is dependent upon the visual and kinesthetic modalities. Varying the gain on the visual display can vary the visual threshold thus varying the effective time constant with a resultant effect upon precision of vehicle control. The addition of motion to the simulator provides stimuli to the motion sensors. This addition may be such that movement is sensed by the motion sensors prior to its being sensed by the visual sense. That is, the effective time constant for the motion sensors may be of a lower value than that of the visual. This earlier detection of the movement of the vehicle allows for the possibility of greater precision of control by the operator.

The effective time constant concept is a means of explaining and predicting how control performance may vary as a function of the "strength of signal" to the several modalities. It also provides some insight into how the visual and motion parameters may interact with the vehicle dynamics.

1.5 CUE POSTULATIONS: TWO ANALYTIC BASES

In setting up an analytic basis for the postulations of cues and recommended research it seemed evident that greater generality of findings would be obtained if a frame of reference for aircraft control were evolved within which the cue taxonomy could be fitted. The frame of reference which was adopted was one in which aircraft control was sub-divided into four major categories. Within each of these categories, cues to control could be postulated in keeping with the sets of cues listed in the previously discussed taxonomy.

The categories of control are: 1) control about the longitudinal, lateral and vertical axes of the aircraft, i.e., attitude control; 2) control of the aircraft along the axes of three dimensional space, i.e., position in space; 3) control of the aircraft state, i.e., its mechanical condition; and 4) mission-related control, e.g., reconnaissance. Within each of these categories the analysis was designed to develop postulates as to cues available to the pilot. As a basis for making the postulations, relevant literature, pilot interviews, investigator experience and analytic examination of the aircraft dynamics and equations of motion have been considered.

The first analytic basis for cue postulation may be considered in terms of information in stimulus dimensions. This was termed the stimulus environment approach. This approach attempts to specify the physical energy spectra of the aircraft system and its environment which are available to and sensible by the pilot. The ability of the human to discriminate changes within each energy spectrum is then examined to determine those cues in the environment which the pilot could use for aircraft control. Following the specification of physical energy spectra, it is necessary to determine which cues are actually used for control. This approach was deemed to have utility in examining the auditory cue problem.

The second analytic basis for specification of cues was considered in terms of information displayed as an array of cues, or the information array approach. This approach was deemed to be most useful in postulating cues in the visual, motion and control movement areas. With this approach, rather than beginning with a specification of the physical energy spectra, postulations are made as to which cues are present and needed for control and then the stimuli are sought which give rise to these cues so that they may be described and quantified. It should be remembered that both approaches are aimed at identifying and describing the physical, quantifiable parameters which provide stimulus sources for the cues. The stimulus environment approach is employed by describing the whole of the physical environment and distilling from it those stimuli which provide the basis for aircraft control. The information array approach is employed to postulate the cues which are present and used by the pilot in control followed by a specification of the physical stimuli which provide these cues.

2.0 VISUAL CUES

2.1 INTRODUCTION

In Chapter 1.0 an analytical approach was adopted which developed a taxonomy for classifying cues within dimensions of aircraft control. In this chapter visual cues are postulated within the framework of the taxonomy and experiments are recommended for testing the validity of the postulates.

Several major questions relevant to the problem of the contact world visual cues in ground based trainers are considered here. These are questions of (1) monocular cues, (2) binocular cues, (3) display content, (4) color vs black and white, (5) display field of view, (6) virtual imagery, and (7) visual image quality.

2.2 BACKGROUND

2.2.1 Referents and Controlled Indices in Visual Control

A major consideration in the postulation of cues discussed in Chapter 1.0 was that, when cues for control are postulated, it is implied that there exists a desired condition or standard to which system output is being compared or controlled. This standard was termed the referent. Control also implies a controllable index which the pilot seeks to maintain in some position relative to the referent. Therefore, in specifying cues to control, those elements in the stimulus which provide both the referent and the control index must be specified. Note that this would not apply to realism or masking cues.

In the visual modality the referent or standard may be an identifiable element in the real world whose physical characteristics may be described as providing the stimuli for the cue, e.g., the horizon line as a referent for aircraft. In the motion and auditory senses these referents may be more subjective in that they are remembered standards for which the objective real world stimulus elements are not always present when control judgments may be made.

The visual judgment tasks approximate the subjectivity of the motion and auditory tasks under those conditions in which a rate must be remembered or the controlled index must be kept in some learned juxtaposition relative to the referent standard. Under these conditions a controlled index may be required to be placed in some relation to an external referent. For example, it may be necessary to keep the nose of the aircraft a certain distance below the horizon for level flight. Thus, in contact flight the relationship between the standard and the controlled index may often be a learned and remembered separation distance rather than a super-imposition of indices. As such, this relationship is subject to forgetting and, over a period of operation, subject to drift in much the same manner as auditory standards drift. This drift of the visual referent has been demonstrated by Thielges and Matheny (1966). It is important, therefore, in identifying the referent and the controlled index that the spatial relationship between these two be identified and made explicit.

Another important consideration in the postulation of the cues and the interactions among cues between the various sense modalities is the dynamic aspects of the stimulus energy which gives rise to the cues. The position of the controlled index relative to the referent is important but of equal importance are the time derivatives of that position. The learned rate of movement of a physical element may serve as a standard against which the rate of a controlled index is judged and controlled. The rate of movement of the nose of the aircraft around the horizon or the rate of flow of ground beneath the aircraft may serve as important cues for various control decisions. It should be noted that when the task is control of the rate of movement of an element through use of the visual sense, the standard or referent may be required to be stored and is subject to the same problems of drift as are the more static referents in the motion and auditory senses.

2.3 MONOCULAR CUES

2.3.1 Perspective Geometry as a Useful Descriptive Method

One of the difficult problems in postulating visual cues is the setting up of a set of constructs which operationally and rigorously define the visual world scene and can be systematically varied in order to determine the effect of variations upon operator performance. An operationally defined set of constructs could be generated from an examination of the pure physics of light and the visual discrimination ability of the human, i.e., the stimulus environment approach discussed in Chapter 1.0. That approach to the identification and specification of the visual cues was found to be rather sterile in that the microscopic examination of visual stimuli did not lead to postulates as to how the pilot perceives and obtains information from the real world for control of his aircraft.

The information array approach has proved more productive of postulates provided the requirement is kept clearly in mind that the stimulus energy giving rise to any postulated cue must be stated in explicit quantifiable terms. This approach draws upon the experiences of the investigators, pilots and users of trainer visual attachments for postulates as to visual cues for aircraft piloting. Consideration of the information from these sources centers attention upon the role of monocular cues in aircraft piloting. It is important to examine the role and the adequacy of monocular cues for ground based trainers because of the relatively simpler equipment problems in generating monocular displays compared to binocular displays. Further, if monocular cues can be found effective for control and for training, simple perspective or picture plane geometry describing the single eye scene may be applied to the problem of cue description.

The monocular cues commonly listed (Graham, 1966) are (1) relative size, (2) interposition, (3) linear perspective, (4) aerial perspective, (5) monocular movement parallax, (6) light and shade, and (7) accommodation. While these cues are proposed as being those which allow for judgments of depth or perception of space we are interested in a set of cues which allows the pilot to do more. He must not only make judgments as to depth or distance but must make judgments with respect to the attitude and position of his aircraft within that space. Thus, those cues which serve as referents and control indices which enable him to make judgments as to attitude and position as well as distance are necessary.

Examination of the list of monocular cues given above leads to the conclusion that, with the exception of light and shade and accommodation, the perspective geometry methods are applicable to their quantitative description. The use of such a descriptive method makes possible the quantitative specification of the position of points, lines, planes, and therefore objects, in visual space so that their number and relationships may be systematically stated and varied as independent experimental variables. In particular, it allows for the expression of the relationship between referents in the geometrically described real world visual space and the indices which are a part of the aircraft being controlled.

The important consideration would appear to be that a perspective geometry analysis is an abstract method of mathematically treating retinal stimulation which can prove useful in programing on a two dimensional display the visual cues derived from a three dimensional scene. The analytical treatment of these cues must necessarily be limited by the basic assumptions underlying the perspective analysis method.

A description of the application of perspective geometry to the problem of cues to aircraft landing is given by Bell (1951). An intensive analysis of its application to the cues to control of the helicopter during hover is reported in Matheny and Thielges (1965). These reports demonstrate the manner in which a perspective analysis is useful for mapping the visual area available to the pilot, for describing the relationships among objects, and calculating rates of movement as a function of the angle of regard for given dimensions of aircraft control.

2.3.2 The Adequacy of Monocular Cues

Before postulating a set of monocular cues for the pilot and the adoption of perspective geometry as a dimension along which they may be described and varied, the literature dealing with binocular and monocular cues to depth perception as it pertains to piloting was examined.

The adoption of a perspective geometry approach for the two dimensional description of the three dimensional world sets certain bounds upon the cues which can be postulated within this framework. That is to say that perspective geometry does not consider other dimensions of visual perception such as color, brightness, or attenuating factors. (These dimensions are considered later in this Chapter.) Within the perspective geometry framework, however, a multitude of postulates as to relevant cues may be made, tested, and used as the basis for trainer visual attachment specification.

As a prelude, the literature supports the conclusion that, in those situations in which the aircraft pilot is required to exercise control using visual cues, monocular cues are sufficient for most conditions of control. One of the earliest to concern himself with the problem of monocular and binocular cues was Woodworth (1945). He concluded that "except for close work, the manipulation of small objects right before the eyes, binocular cues are probably less important than covering, shading and the different kinds of perspective."

The literature dealing specifically with the control of aircraft under both binocular and monocular conditions suggests also what might be predicted from the results of laboratory work. That is, any superiority of binocular over monocular discriminations is most evident for near objects and decreases to equality at distances at which most visual discriminations are made by pilots. (Hirsch & Weymouth, 1947; Graham, 1966, pp. 525).

In the introduction to their recent study Lewis and Krier (1969), report some interesting statistics provided by Dr. Stanley Mohler of the Federal Aviation Administration. These statistics from FAA files indicate that during the last five years no one-eyed pilot has been involved in a flight accident related to vision even though more than 2600 were flying as of 10 December 1968. These data support the "Wiley Post"[1] type of anecdotal evidence in support of the adequacy of the monocular cues for aircraft control. It is interesting, however, that such a large number of pilots are currently carrying out accident free flying using only monocular cues.

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[1] It may be necessary on this, the 35th anniversary of his death, to point out that Wiley Post was a famous one-eyed pilot of the 1930's.

The Lewis and Krier study deals directly with the question of the adequacy of monocular cues for aircraft piloting. In this study pilots flew the jet trainer during a series of touch and go landings. Landings were carried out with full binocular vision followed by landings with first the left and then the right eye covered. No differences were found in performance across these conditions with respect to measured longitudinal deviation from a specified touchdown point. Differences were found with respect to airspeed control, sink rate and approach angle. Under monocular conditions the pilots tended to fly steeper approaches than under binocular conditions, although none of the pilots were aware of this at the time. The steeper approaches were reflected in differences in airspeed, sink rate and approach angle.

In a study carried out by NASA and discussed by both Perry et al (1967) and Roman et al. (1967) pilots flew the T-33A aircraft to successful landings with such a narrow horizontal field of view that stereopsis could not have been used during the landings. There was, however, no significant decrement in pilot performance as the visual cues changed from binocular to monocular.

Brown (1970) measured the performance of two pilots during twelve approaches with binocular and twelve approaches with monocular vision during night landings. Measures of performance were rate of descent at touchdown, distance beyond the ILS transmitter at touchdown, lateral velocity at touchdown, and bank angle at touchdown. The authors report the use of monocular vision at night, while causing changes of flight technique, did not generally produce poorer landing performance.

Wilkerson and Matheny (1961b) found that in hovering a helicopter there was no difference with respect to average altitude error between the monocular and binocular conditions. There were, however, significant differences in the control of lateral and fore and aft translation.

In an early study by Pfaffmann (1948) experienced Naval flight instructors carried out a series of landings while wearing special goggles which cut out the binocular stereoscopic field of view. The evidence from this study showed that the removal of binocular visual cues impaired the landing performance by introducing a constant error, i.e., the tendency to level off too high. As in the Lewis and Krier study there was some tendency to approach too high. This problem was accentuated by the fact that there was a tendency to crowd the downwind leg closer to the field because of a feeling that the size of the objects and buildings around the field appeared smaller under monocular conditions.

The studies of Brictson (1966) are relevant to the question of monocular versus binocular cues. A large number of carrier recoveries (landings) were carried out both during the day and at night. Under night time conditions the pilots were operating under conditions in which binocular cues were reduced. Pilot performance during day and night landings were found to be different in terms of altitude errors while lateral errors were essentially the same for the two conditions. In general the pilot tended to approach slower and higher and to land harder and shorter by day then by night with greater night performance variability in all measures.

The early work of Roscoe (1948, 1951) is relevant to the problem of binocular versus monocular cues. In Roscoe's first experiment (1948) pilots made landings to a spot using a periscope display which presented the information to the pilot on a flat plate display of restricted size. In this experiment, although the pilots could successfully accomplish the landings, their performance was significantly worse under monocular conditions than when their view was unrestricted and binocular. Roscoe attributes these differences to the combined effect of the loss of binocular cues and restriction in total visual field. In his discussion of the results Roscoe states "it is possible that the binocular depth cues as such are of significant importance. This could be tested early in another experiment simply by covering one eye and comparing the accuracy of the landings made in this condition with results from the condition 'C' (the unrestricted binocular condition). It is doubtful that the difference would be significant."

In a later experiment Roscoe (1951) compared performance of pilots in flying the "oboe" flight pattern using a two dimensional "periscope" to flight using the unrestricted contact display. As one of his primary conclusions Roscoe found pilot performance with an eight inch square "periscope" display not to be significantly different from that achieved under conditions of contact visibility.

In one of the few transfer of training experiments relevant to the problem Payne, Dougherty, Hasler, Skeen, Brown and Williams (1954) used a two dimensional landing display in which a perspective projection of the runway was viewed by the experimental subject as a projection on a translucent screen. The perspective projection of the runway varied as a function of the aircraft's heading, altitude and distance from the runway. Payne et al. found that this display system gave the pilots no cues as to when to start their round out or to accomplish their touchdown. Therefore, the device was used only to study transfer of training in making an approach to landing in the SNJ aircraft. Students were allowed, however, to continue their approach to a touchdown during their transfer trials in the actual aircraft. The results showed that the students who were trained using the two dimensional landing display required 61% fewer trials in the aircraft and made 74% fewer errors than did the students who did not use the device. The authors emphasize that the device should be used as a medium for principles training. By this they mean that the device is regarded essentially as an analog of the final task. An important part of the technique of using it is making the analogy clear to the student. The technique attempts to indoctrinate the student in the variety of relevant cues or "signals" during the course of the task, and to make clear to him what constitutes a correct sequence of conditions. The point is made that when a device is used as a principles trainer it may depend less heavily for its success upon faithful simulation of the final task than does a device simply used as a task sample.

Finally, we may cite the conclusions of Cibis (1952) as follows: (1) the most reliable visual perception of space is obtained by observing an unobstructed homogeneous surface with simultaneous action of stereopsis, linear perspective and motion. (2) Stereopsis associated with linear perspective by exclusion of the cues derived from motion yields almost the same degree of reliability. (3) Stereopsis without the effectiveness of linear perspective but with cues resulting from motion is less reliable than linear perspective under monocular test conditions. (4) Depth perception is least reliable under conditions involving motion but excluding linear perspective and stereopsis.

Of particular importance is conclusion (3) in which the importance of linear perspective would appear to be emphasized and is fundamental.

Summarizing the literature it is apparent that, although the evidence is not always clear cut in favor of monocular cues, it does support the notion that a profitable area of research would be to determine that set of necessary and sufficient monocular cues which the pilot can and does use in controlling his aircraft throughout the several dimensions of control. We should hasten to point out that the evidence for the utility of monocular cues lies in those perceptions in which the stimuli are distant from the observer. In certain piloting tasks such as hovering the helicopter in which stereopsis might be quite beneficial the evidence is somewhat equivocal (see Wilkerson & Matheny, 1961b). This is discussed in more detail in Section 2.4, Binocular Cues.

Within the framework of perspective geometry, cues may be postulated through explicit statement and tested by observation of the effect of their being varied upon pilot control behavior. For example, the relationships among points, lines, planes or solids which provide the cues to height and distance from a point on the ground may be stated explicitly.

Using this frame of reference, postulates as to monocular cues for control of aircraft attitude and position in space have been made and are contained in Appendix A.

2.4 BINOCULAR CUES

It was suggested in the discussion of monocular cues that most visual cues used by the pilot are beyond the range at which binocular cues could be used. While, as a general finding, the literature supports this suggestion, there is evidence that in certain tasks the pilot may make use of near distance information in which binocular cues are used, if not as primary cues, at least to serve to increase the accuracy of near distance perceptions. For example, Wilkerson and Matheny (1961b) and Brown (1970) found that variability in performance increased significantly during conditions of monocular cues over that during binocular conditions although average level of performance was not different. In both of these studies near distance cues could be involved since Matheny and Wilkerson studied helicopter hovering and Brown studied aircraft landings. In Brictson's work (1966) with carrier landings the greater variability in altitude error under night (monocular) conditions is also evident.

Graham (in Stevens, 1951) indicates that convergence as a cue is not effective beyond about 20 yards. Stereoscopic vision using disparate images has a theoretical limiting range of about 495 yards. However, these values have not been outstandingly helpful in making decisions about visual attachments.

The usefulness of near vision binocular cues for the task of helicopter hovering should be established for guidance in future trainer design because of the criticality and difficulty level of that task (Matheny & Wilkerson, 1965). Research on the problem should establish the contributions of binocular cues to performance and the degree of transfer from the monocular training conditions to the binocular operational work. It is believed that equipment suitable to the conduct of this research is available in the tethered devices such as the Jaycopter and the Whirlymite. Descriptions of the recommended research are given in the following Sections.

2.4.1 Recommended Research on Near Distance Cues.

A tethered helicopter type device such as the Jaycopter allows enough freedom of movement and opportunity for performance recording to carry out useful research on the low altitude visual cue problem. Most importantly it provides the motion cues coincident with the visual. As a criterion device it is relatively low-cost and manageable as a research tool.

The experimental question to be answered is the value of the binocular visual display over the monocular in the ground based trainer. The experimental variable may be varied through requiring the subject to perform the hovering task, both binocularly and monocularly. Using the time savings transfer paradigm in which time to reach criterion by an experimental group is compared to that required by a control group, the monocularly trained group would be treated as the experimental group. After training to criterion in holding altitude and ground position they would be transferred to the criterion condition in which they perform binocularly. The control group to which the experimental group is compared, learns the task to criterion using binocular vision.

The Jaycopter as a research tool may be adapted also to the investigation of other visual cues of importance to ground based trainer design for near distance tasks. For the hovering task the variables of display content and extent of visual field may be systematically investigated. The study of display content requires that an enclosure be constructed about the device upon which may be placed the picture plane representations of the real world objects in accordance with the rules of perspective geometry. The enclosure surface must be capable of being changed from a flat to a curved display surface. A floor must be constructed under the device upon which ground "texture" may be represented. Content of the display may be variable in providing (1) attitude referents, i.e., horizon line and ground plane (2) altitude referents, i.e., objects on and protruding above the ground plane and (3) ground position referents, i.e., objects on the ground plane. The postulates and laboratory findings of Matheny and Thielges (1965) with respect to external and internal referents may be tested with such a device.

Research bearing upon the question of how visual space may be best described for aircraft control may be possible of being undertaken in the tethered helicopter device. This research is concerned with the considerations raised by Luneburg (1950) and Blank (1959, 1961) as to how visual space is best represented. These considerations may be important to the design of ground based visual attachments. As viewed by Luneburg and supported by Blank, visual space is best described as Riemannian space with constant Gaussian curvature. It is recommended that an intensive investigation be made of the degree to which the tethered helicopter with appropriate curved and flat display surfaces can be used to test Luneburg's theory of visual space under dynamic viewing conditions.

Another most important area of investigation is that of the utility of binocular cues in judgments of altitude when the observer is moving approximately parallel to the ground at rates of speed representative of those just after round-out and before touchdown in fixed wing aircraft. It may be hypothesized (and has been suggested in the literature) that the "rate of flow" of objects in peripheral vision is a necessary and a sufficient cue for altitude judgments at this distance.

The use of a light plane or helicopter to obtain quantitative comparison data between monocular and binocular conditions is recommended. However, the appropriate textural content question may be raised particularly by those concerned with computer graphic display content generation. What density, size and contour of objects constitute texture can be argued but will not be here. Rather it is evident that position and shape of textural elements may be described by the rules of perspective geometry and varied as an experimental variable.

As an experimental tool of general use in obtaining answers to many visual attachment questions, and the display content question in particular, it is recommended that a model-terrain high-resolution television projection system be procured. Such a system has the flexibility required of a research device in that the terrain content may be varied systematically from "stylized" computer graphics types of displays to more real form types. Other capabilities of such a system for use in the study of other questions will be discussed in the sections to follow.

2.5 THE ROLE OF COLOR AS A VISUAL CUE

Whenever visual cues to flight control are discussed or the requirements for visual attachments to ground based trainers are considered, color is nearly always advanced as being a parameter of importance in providing the operator with his necessary information. In addition to information concern with color as a cue, formal statements appear in such publications as Society of Automotive Engineers, Aerospace Information Report, AIR-771 entitled "Visual Simulation for General Flight Simulators/Trainer Attachments". In this report the desirability of the additional cues furnished by color is stated. Ketchel and Jenney (1968) indicate that contact analog and terrain avoidance displays could profitably make use of color to improve perspective or to create quasi-three dimensional effects. However, there is no evidence to be found in the literature which indicates that color has any of these attributes.

Concern with color as a visual cue to direct aircraft control is probably unjustified. Rather, when the role of color as a cue is considered it must be examined in terms of the indirect effect of some of its dimensions upon the perceptual judgments required of the pilot. To the extent that color improves contrast or apparent brightness it may influence judgments of distance. For example, Taylor and Sumner (1945) found that the brighter colors used in their experiment (white, yellow, and green) were judged to be nearer than the darker ones (red, blue and black). However, the lack of any evidence that color contributes to the judgments required of the pilot in controlling his aircraft leaves the problem of this dimension of visual cues in need of experimental investigation.

The apparatus suggested in Section 2.4 in which a terrain model is used with a television pick up and T.V. projection display system makes possible the study of identical tasks in the simulator with and without color. It is recommended that this dimension of visual cue encoding be of relatively low priority in view of the lack of any positive evidence indicating that color can be used as a cue to control. On the other hand, color will undoubtedly be felt to be of importance by users of the devices in order to add realism to the display with the resultant motivational value contributed by its addition. The problem of color must then be faced frankly as one in which its utility as a cue to control must be established definitively. If it is found not to be a significant contributor to control it should be recognized as being used solely for enhancing the acceptability of the device. Whether acceptability of a device has a direct and significant effect upon the effectiveness of the device is another experimental question. This acceptability effect and its integrative effect upon motion cues is discussed in Chapter 6.0.

2.6 VIRTUAL IMAGERY

Proceeding with the argument that the majority of the visual cues of importance to the pilot are those which are at a distance sufficient to make them monocular implies that the lines of sight of the two eyes are parallel with identical images falling upon each of the retinas and that the viewed object is at virtual infinity. This set of circumstances has lead to the supposition on the part of some designers of ground based trainers that the visual scene of the pilot may be displayed as a virtual image, i.e., presented by some form of collimated light system.

Evidence with respect to the advantages of such a system either in terms of more closely approximating the real world visual cues or as a contributing parameter to training devices is not available. Brown (1970) found no differences in touchdown performance between a T.V. image viewed at 2 feet and an image created by a lens system which produced a virtual image nearly 6 feet away. However certain questions may be raised with respect to virtual display imagery which need empirical investigation.

One of the first problems is that in a collimated system all objects projected by the system presumably are projected at infinity. This may not be desirable particularly with respect to the ground plane on which viewed objects rest since this ground plane presumably extends from immediately below the individual to infinity at the horizon. Consequently, it is postulated that near points on the ground plane should not always appear at infinity.

Another problem suggested with respect to virtual imagery but not verified conclusively during this investigation is that with collimated systems of larger exit pupils the apparent distance of an object changes as it moves away from the central line of regard. That is to say that while an object viewed directly forward along the medial plane will be seen as being at infinity, as that object moves laterally in the visual field it will appear to come closer to the observer due to the optics of the system. The empirical investigation of these phenomena must be undertaken and definitive data obtained as a first step in the investigation of the utility of virtual image displays.

A sometimes bothersome problem which is becoming less of a nuisance with the advancement of the state-of-the-art is that of exit pupil size. However, it would appear that the exit pupil size is related to the problem mentioned above in that if the exit pupil is small the apparent change in distance as a result of lateral movement in the visual field is less than when the exit pupil is large. Again, this is a question requiring empirical investigation.

As a summary statement, it is recommended that the question raised regarding the relationship between the apparent distance of an object and its position in the visual field of a collimated display be investigated and empirical data obtained. Following these investigations the comparative effectiveness of using virtual imagery as opposed to flat plane two dimensional projections for distance viewing should be investigated with flat planes positioned at near (less than 5 ft.) and far (greater than 20 ft.) distances. It is the hypothesis of these investigators that the differences would not be significant or practical and that the additional complexity of creating virtual imagery would be unnecessary. This hypothesis requires empirical test.

2.7 FIELD OF VIEW

The required field of view for the visual display or projection screen for a ground based trainer is a parameter that must be considered as dependent upon other parameters of the training situation. First of all, it is important that it be considered as a function of the dimension of control of one dimension of the vehicle. For example, roll may be more effectively obtained from one area of the visual scene than from another. Similarly, information with respect to altitude control may be obtained more effectively from one area of the display than another. These suppositions rest upon the assumptions made earlier in Chapter 1.0 that the relevant cues for control rest upon the existence of external referents on the ground plane or horizon and some perceived relationship of an internal referent on the windscreen to that external referent.

Matheny and Thielges (1965) developed a model whereby the precision of control for any dimension of control of the vehicle, e.g., the helicopter in hover, could be predicted as a function of the relative placement of the internal and external referent within the field of view. Experimental evidence reported by Thielges and Matheny (1966) verified the model predictions with respect to the detecting of a displacement of a referent within the field from an internal referent on the windscreen during the hovering of the helicopter. This model did not deal with detections of rates of change of the vehicle or the use of such rate information.

A variety of reports provide evidence pertinent to the required extent of visual display. Roscoe's "Flight by Periscope" studies (1951) show that, while performance varies as a function of the width of the display for very small displays, i.e., from 2 inches up to 8 inches, performance with an 8 inch square attitude display was not significantly different from that achieved with contact visibility. The description of Roscoe's apparatus indicates his 8 inch square attitude display gives a field of view of plus or minus 15° laterally.

Experiments conducted by Matheny and Hardt (1959) using static displays demonstrated that the size of the display did not differentially affect the interpretation of pitch and roll in a contact analog display for display sizes of 4 1/2 inches, 11 1/2 inches and 42 inches square. Wilkerson and Matheny (1961a) found also that there were no significant differences in attitude control of the helicopter during hover when using an 8 inch square display or viewing the scene under full contact conditions. At the nominal viewing distance in the helicopter of 30 inches the 8 inch square display used by Wilkerson and Matheny would provide a viewing angle of plus or minus approximately 7 1/2 degrees.

With respect to the control of such aircraft dimensions as position relative to a point on the ground or judgments of altitude above the ground Roscoe measured performance in both right climbs and left glides while Wilkerson and Matheny (1961a) measured the ability of the helicopter pilot to maintain ground position and altitude during hover. Again an 8 inch square display was sufficient to provide the pilot with information which allowed him to perform as well as with the full contact world view.

Considering the visual capacities of man, data relevant to his visual acuity as a function of angular distance from the center of the fovea (Graham, 1966, pp. 329) indicate that increasing the lateral dimension of the display beyond approximately plus or minus 5° would bring about no significant change in the operator's abilities to detect changes. However, when one turns his attention to the other component of the system, i.e., the dimensions of movement of the vehicle, it can be demonstrated that there is a direct and relevant relationship between dimension of control of the vehicle and the dimensions of the visual display. This is best demonstrated by considering first the dimension of control of pitch of the vehicle. It can be seen that, if the horizon line is used as an external referent and a point on the windscreen of the vehicle is used as an internal referent, a very narrow forward view is sufficient for detection of pitch changes. The width of the forward view would have no effect upon the relationship between internal and external referents with changes in pitch. However, when the control of roll is considered it is apparent that a very narrow forward view using the horizon as a referent and a point on the windscreen as an internal referent would give little information with respect to roll. As the width of the viewing area is expanded the linear displacement between the horizon and any given internal referent would increase for any given angle of roll. Thus, the gain (K) of the display with respect to the roll dimension is increased with the increased width of visual display.

The model developed by Matheny and Thielges (1965) describes the relationships between dimensions of control of the vehicle and placements of the internal and external referents on the X and Y coordinates of the visual display. The model demonstrates that different areas of the visual field are more effective for providing information for the several dimensions of control of the vehicle.

While it has been demonstrated that the ability to detect changes and to effect control of the various dimensions of the aircraft are a function of the size of the visual display, the evidence would indicate that the size is not a critical problem for detection of displacements. It may be postulated, however, that the rate of flow of information as detected either foveally or peripherally is an important cue for the judgment of altitude above the terrain. This has been suggested by Calvert (1957) as his "parafoveal streamer theory" in which judgments of rate of closure and altitude (particularly with respect to glide path) are a function of the flow of objects past the observer as he approaches the ground plane. The experimental question is whether or not the flow of visual stimuli at the periphery provides the useful cue to the judgment of altitudes during tasks such as landing or low altitude flight. The important variables for these judgments are suggested as being the extent of the size of the solid angle of the visual display, i.e., the area of peripheral vision, and the configuration of the ground plane, i.e, the density and shape of the "textural" elements which define the ground plane. Research relevant to this problem is very much needed.

A problem which may be raised and which should be considered here is that of the "minification" phenomenon first suggested by Roscoe during his periscope studies. Roscoe observed that when objects were observed through a lens system with projection on a flat screen of limited dimensions (8 x 8 inches) their judged size was smaller than when observed under contact conditions. This minification effect has not been explored to determine whether it is a function of the two dimensional projection or the size of the surround or some interaction of the two. Although it may possibly have an effect upon the perceived size of objects projected on a visual attachment to a ground based trainer, it is believed that with the screen sizes involved minification is not a problem.

2.8 VISUAL IMAGE QUALITY

The term image quality is used here to cover characteristics of the displayed image such as resolution, contrast and acutance. These measurable aspects of the image may be related directly and predictably to perceived size, or relative position distance of objects within the display. The problems of defining the criteria for the physical characteristics of a visual display in meaningful and relevant terms have been discussed by Rosendahl (1968, 1969) and Maldonato (1968). These are problems which are truly psychophysical and require for their solution the cooperative effort of physicists and psychologists.

The measurable image quality of apparent most concern is that of resolution judging from the space devoted to it in the literature. While resolution, as a quantifiable and measurable parameter of a given displayed image, is an important dimension of the visual display little is known about what optimum or minimum resolution is necessary for any given training device. Nor is it known how display resolution interacts with the content of the display or with other display parameters to influence the training effectiveness of the device. Such question are raised and discussed by Oharek (1967) and by Aronson (1968).

A dimension of visual images which may interact importantly with judgments of depth or distance in a display is that of the acutance or the sharpness of edges within the displayed image. This concept has been discussed by both Rosendahl and Maldonato, (ibid). This "density gradient," as it were, at the edges of objects making up the content of the display may be hypothesized to have a pronounced influence upon judgments of relative distance between objects or of distance of objects from the observer. How the acutance value may be modified by different figure-ground brightness or color contrast ratios is another interesting and unexplored question.

Although resolution, acutance or contrast ratio per se within a display may not properly be considered as cues to control in the sense we have been using that term, it is important that their interactive effect upon cue identification and discrimination be considered.

2.9 UNUSUAL VISUAL CONDITIONS

A ground based trainer can be visualized as being used in such a way as to provide training by presenting first the essential relevant cues for normal flight and gradually complicating the cue discrimination task through the introduction of noise or masking. This gradual increase in the requirements of the task should include, at its final level of difficulty, the visual perception task which requires the pilot to perform under unusual and stressful conditions or high work loads.

One of the most common of the "unusual" conditions is that of the requirement for the pilot to make judgments with respect to his spatial position and vehicle attitude upon breaking from low ceiling conditions with limited runway visibility. The variables of the visual display discussed in the previous sections should be investigated with respect to pilot performance under these unusual conditions and of breakout from instrument to contact flight. The importance of being able to train in this task in the simulator rather than the aircraft is evident.

A further unusual condition which requires investigation is the interaction of the parameters of the visual display with the motion cues with the result that the pilot becomes disoriented. This interaction is discussed more fully in Chapter 6.0, Interactions Among Cues.

3.0 MOTION CUES

In consonance with the purpose of the project of providing an analytic basis and experimental designs for the conduct of research on multi-sensory cueing, postulates as to cues to motion along with recommended research are presented. Postulates as to cues are based upon considerations of the results in the physiological, psychophysical, and behavioral sciences literature. The findings in these areas have been brought together to form an important background for the understanding and justification for the postulates presented. Experiments are outlined which are designed to test the validity of the hypotheses and lead to their verification or modification. Consideration of the physics of motion and a description of how the motion characteristics of objects may be expressed has been important to the formulation of a precise description of motion as an independent experimental variable.

In order to determine the cues which comprise the motion information array it is necessary (1) to deliberate the functional role of motion reception in the human, (2) to examine what is presently known concerning the human motion sensory receptors and (3) to speculate on control laws which govern the interaction of these receptors, the perception of motion and the resultant reaction of both the motion perception and reflexive responses. The elements (1), (2), and (3) constitute the bases for the building blocks of the control system. In order to produce an output from any system we must have an input forcing function. The output will be a result of the input to the system and the manner in which the system operates upon the input. Since the human piloting an aircraft is placed in a motion environment somewhat dissimilar from that of self locomotion, the effects of such a dissimilarity upon motion perception should be discussed. Figure 3-1 illustrates the outline of the Sections 3.1 - 3.3 of this Chapter. Certain research hypotheses concerning the implementation of motion cueing in flight simulators are derived from these deductions concerning motion perceptions.

In Sections 3.4 and 3.5 motion as an experimental variable is described in terms of its mathematical expression and how it can be manipulated as an experimental variable. In Section 3.6 experimental work and the requirements for equipment capability and calibration are outlined.

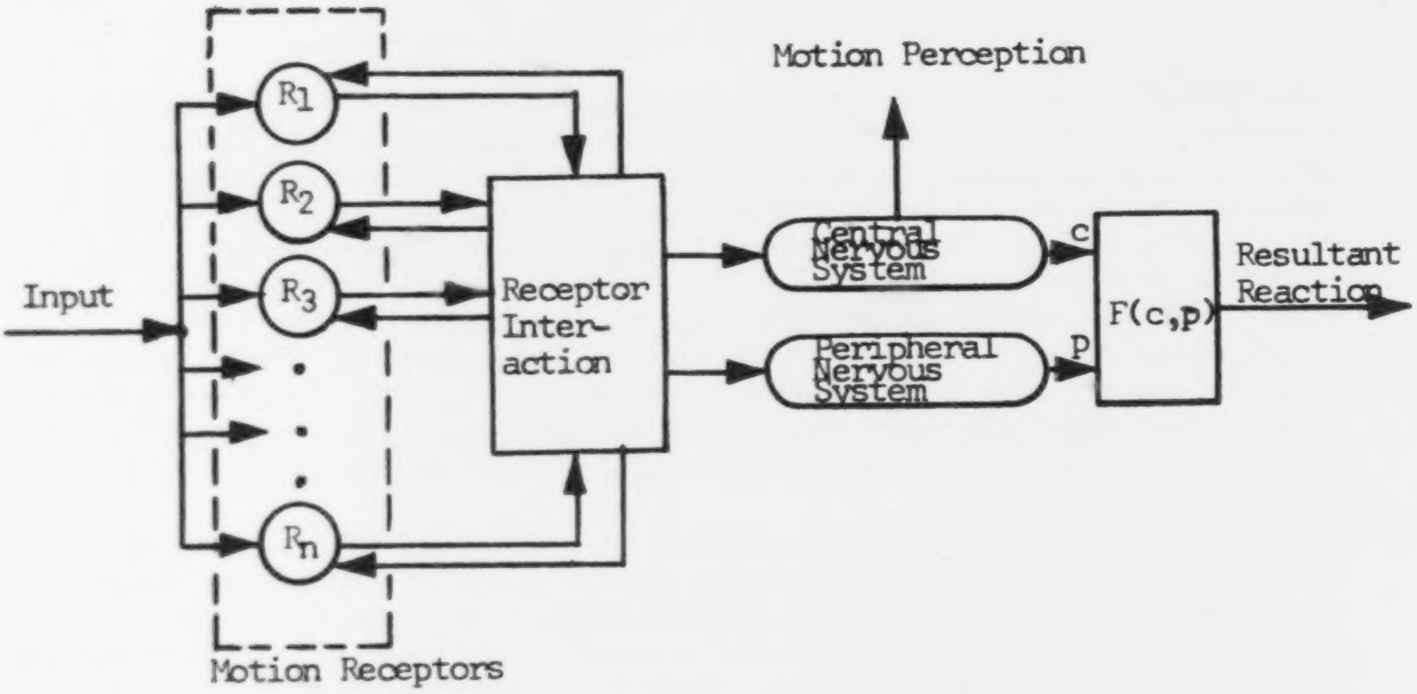

Figure 3-1. The Motion Perception System.

3.1 FUNCTIONAL ROLE OF MOTION RECEPTION

The perception of the movement of the organism with respect to its environment involves a complex interaction of many receptors distributed throughout the body. Although consideration of the interaction with the visual sense is basic to the understanding of the flow of physical orientation data within the organism, it is instructive to examine the functioning of the motion receptors in the absence of the visual feedback loop. In this Section this function is analyzed and described.

Perhaps the most basic concept of the functional basis for reception of movement of all or part of the body is that it is for postural stabilization and locomotion. These two principles (postural stabilization and locomotion), although on first impression apparently opposite in nature, are truly extensions of one another. That is, locomotion is accomplished by an alternative unbalancing to produce momentum and rebalancing of the body about a new point of stabilization. Extensive studies of the vestibular system indicate that this system plays a large role in sensation of deviation from the apparent vertical. This role is far from exclusive, however, since the neck joint receptors also appear to make a highly significant contribution to the receptors of motion, particularly to the conscious awareness of motion.

We may postulate that the experienced pilot tends to view the aircraft which he controls as an extension of himself. In this sense we may use the concept of the aircraft as an "exoskeleton" with the pilot contained in the "coelomoid." The concept of the vehicle as an exoskeleton of the pilot may be inferred from the work of investigators of human describing functions, the results of which have indicated that the combined describing function, Yp Yc, is adjusted by the pilot in a generally predictable manner. In these experiments, the terms Yp and Yc are used to indicate the describing functions of the pilot and the controlled element (such as the aircraft), respectively. In other words the pilot-vehicle combination becomes the essential unit. This recent (in the evolutionary sense) exoskeleton has performance capabilities not completely compatible with the sensory apparatus which has evolved in man in the course of time. For the visual sense this lack of compatibility has been compensated through the design of flight instruments as visual aids. However, except for the kinesthetic cueing through the control feel system, man must rely upon the responses produced by his natural uncompensated sensory receptors for body motion information.

The second basic function served by perception of movement of the body is to produce a relatively stable image of the visual scene upon the retina. Meiry (1966) studied extensively the effect of stimulation of both the vestibular apparatus and the neck proprioceptors upon compensatory eye movements. Both of these functions have been shown by Mayne (1965) to be matched dynamically to the frequency bandwidth of the natural movements of several animal species. The conclusion may be drawn that a large percentage of disorienting phenomena occur when the displacements to which the animal is subjected exceed in magnitude, frequency or both, the "evolutionary design" limits of the motion sensitive organs. Although aircraft have been basically designed for the capabilities of the human, there are many motions of the aircraft beyond the realm of "natural" human movement. Examples which can be cited are the large excursions in the vertical dimension or the slow, continuous turns with prolonged apparent vertical misaligned with the inertial gravity vector.

3.2 THE MOTION RECEPTORS AND RECEPTOR INTERACTION

3.2.1 The Non-Visual Receptors.

In the literature concerned with the role of motion in aircraft control the weight of investigation has been placed upon the role of the labyrinthine receptors. The structure and function of these devices are apparently so well understood that a high degree of accuracy has been developed in their mathematical description. A mechanical analog of the vestibular system has been built (Young, Meiry, Newman, & Feather, 1969).

While such an effort is commendable, it may be that such emphasis on a particular system has led to the disregard of other sensory mechanisms which could be equally important to the perception of necessary motion cues in aircraft control. If these other sensory systems are overlooked, the influence of their dynamic range is, consequently, omitted from analysis. It is a good design principle to match the frequency bandwidth of receiver to signal if distortionless reception of a signal is desired. Consequently the inference that has been made that a motion signal produced by a simulator platform should match the bandwidth of the semicircular canals may be only partially correct.

Roberts (1967) has presented a comprehensive treatise on the qualitative interaction of the otoliths, semicircular canals, and neck proprioceptors in relation to the postural muscle response. He has illustrated that the orientation of the head (and as a result the vestibular system) is not solely responsible for the resultant reflex. It appears that the head-neck-trunk relationship considered as a unit determines the reflexive balancing reaction of the animal. The nature of the postural reflex is thought to merit substantial consideration; it is postulated that it is through the activation of the postural reflex system that major contribution of motion to aircraft control precision is made. If this is so, it is imperative to consider some of the aspects of this system, the interactions of its elements as well as the components themselves. The ultimate objective of the understanding of the system would be to be able to utilize the response to stimulation of certain portions of the system to provide motion cues in the flight simulator rather than (as is presently the procedure) reproducing the angular and linear accelerations present at the pilot's station in flight. An interesting initiation into development of a model of the postural control system has been made by Gibson, Edgerton, Haskell and Hill (1969). A set of perturbation equations, based upon LaGrange's equation for a seven element (head, trunk,thigh, shank, foot, upper arm and fore arm) stick man in which each joint is torqued proportional to the joint angle and angular rate, has produced a reasonable approximation to the postural response. The control law which was used, (i.e., that the torque applied to each joint is proportional to the joint angle and angular rate) is based upon a model suggested by Stark (1966) and modified by Agarwahl, Gottlieb, and Stark (1968). In this model the afferent impulse rate from the muscle spindle is shown to be proportional to muscle spindle length and stretch rate for a significant frequency range. Although the validity of such a control law for all the joints in the postural system remains to be established, it appears to be sufficiently reasonable to form the basis for some experimental hypotheses in motion perception and in control movement cueing.

The physiology of the vestibular system indicates that the relative roles of the utricle and semicircular canals are the sensing of linear acceleration and angular velocity respectively (over a specific bandwidth). Roberts suggests that the role of the canals is to provide velocity feedback to increase damping of the motion of the skull in inertial space rather than as a mechanism to provide information concerning the angular velocity of the animal, per se.

The fact that the head-trunk relationship is such a significant one suggests that those elements which tend to produce not only variation in labyrinthine input signals but also variations in the relative position of the head to the trunk (hence the stretch of the neck muscles) should be examined. It has been implicit in many investigations that the body is to be considered a rigid mass so that accelerometers placed near the pilot's normal head position would indicate the acceleration signals imparted to the vestibular system of the pilot. One need only relax the neck muscles and impart a pulse to the body so as to slightly displace the head to observe how loosely the head may be articulated with respect to the trunk. It is the tension of the neck muscles which maintains the balance of the head. The increasing tension of the muscle can be shown to have the analogous effect of stiffening of a spring in that as muscle tension increases the natural frequency of a spring-mass-damper system increases (Agarwahl, Gottlieb, and Stark, 1969).

Support of the skull through tension of the neck muscles is a continuing process unless the individual is at rest. A change in acceleration will alter the load on these muscles, causing the skull to rock. This generates angular accelerations which can be detected by the semicircular canals, linear accelerations which generate a stimulus to the otoliths, and changes in muscle tension in the neck. Through this rocking mechanism the otoliths become useful in detecting linear accelerations applied to the body as a whole. From the combination of signals from all of these receptors the perception of both magnitude and direction of imbalance must be derived. It is not known how these sensors interact or the relative speed of signals reception from each. As previously mentioned the dynamics of the labyrinth have been accurately determined. As Mayne (1965) has suggested, the "natural" body movements of the human are approximated by the bandwidth of the semicircular canals. The electro-mechanical model designed by Young et al. (1969) is based upon the following experimentally derived bandwidths:

Canals	-	0.1 to 10 rad/sec
Otoliths	-	0.1 to 1.5 rad/sec

If indeed, as Roberts suggests, the canals function as rate feedback, the bandwidth of reception of acceleration is increased at the upper end. In addition, if the model parameters measured by Agarwahl et al. (1968) for the spindles of selected muscles of the cat can be hypothesized to be similar to those in the human neck muscles, it can be shown that still higher frequency components can be received. For the cat, a cyclic positioning of the limb (i.e., complex but coordinated paw, elbow and shoulder movements resembling stepping) has been shown to be the response to a cyclic variation in pulse frequency modulation from the vestibular nerve. Furthermore the dynamic response resembles a first order system with the corner frequency matched to that of the labyrinth so that the entire system becomes one in which a limb position correction corresponds to the vestibular (hence head) angular position (Partridge & Kim, 1969). Hence it is postulated that the cue to the perception of motion lies in the awareness of postural tonus reflex to the total motion acceleration signal presented to the body. The evidence indicates that neck proprioception affects the limb response to the vestibular stimulus such that the two signals (vestibular and neck proprioceptive) are multiplicative rather than additive (Kim & Partridge, 1969).

Vibration reception is not limited to the head-to-trunk relationship. Different elements of the body compose the total motion spectrum analyzer. The analogy to the action of the cochlea of the inner ear as an harmonic analyzer may easily be drawn. The coupling between the trunk of the body and extremities other than the head also appears to be a significant factor in the perception of motion cues. In the piloting situation most forces tending to produce accelerations of the body are applied to the trunk by transmission through the aircraft seat. There are, of course, forces transmitted to the limbs directly. These forces include the reaction forces of the controls, rudder pedals and stick, and those reactive forces transmitted to the muscles and joints of the limbs either through vibration or reaction of the limbs against a "stationary" surface with respect to the trunk movement. High frequency, small amplitude vibrations transmitted through the limbs most likely are damped by the body articulation before reaching the head receptors or neck muscles and are transmitted to the CNS by the tactile and joint receptors.

There exists also vibratory motion in the range from 1 to 20 Hz, a frequency band known as the infrasonic range. No reports of the systematic investigation of the effects of this infrasound have been found although it is evident that any auditory noise spectrum which contains components of these frequencies of sufficient power may possibly be transduced through the flight helmet to the head or through conductors in the aircraft body. The higher powered jet engines have noise spectra which show shifts of acoustic energy toward the lower ranges (below 100 Hz) and particularly below 20 Hz (Guild, 1965). There appears to be no reported research concerning the infrasonic spectrum within the cockpit environment. The highest bodily resonant frequency is nominally 11 Hz; evidence exists suggesting that it is at this frequency that visual acuity is most greatly disturbed (Harris & Shoenberger, 1965).

The fundamental vertical resonant frequency of the human body in the sitting position appears to be around 5 Hz with a damping ratio ranging from 0.575 (Vogt, Coermann & Fust, 1968) to 0.167 (Harris & Shoenberger, 1965). It is obvious that any acceleration spectrum which contains sufficient energy at this frequency will cause reception of a signal in the neck muscle tension proprioceptors.

3.2.2 Contribution of Motion to Visual Perception

The most extensively studied aspect of kinesthetic and vestibular proprioception has been its effect upon visual tracking. As Mayne (1965) has indicated, the "natural" body movements of the human, covering the range of approximately 0.04 to 4.0 Hz, are matched by the bandwidth of the vestibular system. The tracking capability of the eye (without motion compensation) appears to be very accurate, within the linear range of eye movement (head stationary), in response to visual input signals which contain no significant frequency components above 1 Hz (Young, 1962). With the addition of vestibular and neck proprioceptor compensation the tracking capability of the eye is raised so that frequencies up to 2.5 Hz may be followed. Meiry (1966) studied extensively the role of each of the compensatory mechanisms of vestibular and neck proprioceptors with respect to both environmental and earth-fixed fixation points in the lateral (yaw) dimension. Environmental fixation, i.e., a state in which the fixation point is stationary with respect to the observer, occurs when the pilot observes a cockpit instrument, the moving portion of which is not stationary with respect to inertial space. Earth fixed fixation, i.e., a state in which the fixation point moves with respect to the observer but remains stationary with respect to inertial space, occurs when the pilot observes a stationary object on the earth (for a short enough duration so that essentially the earth reference system may be considered stationary in space) or when a cockpit instrument dial moves so that it remains fixed in vertical space, e.g., the attitude indicator except when yawing. According to Meiry's experiments, the neck proprioception and vestibular systems have additive property effects upon the eye tracking capability at least over the frequency range tested (0.03 Hz to 2.00 Hz). It will be recalled that Kim and Partridge (1969) have suggested that these effects may be multiplicative for the postural mechanism, although the latter (Kim & Partridge) report does not contain the same mathematical exploration as does Meiry's. It could be postulated that the motion sensed inputs are combined differently for the two physiologic functions.

Compensatory eye movements caused by signals from the vestibular system and neck proprioceptors are reflexive in nature as are those signals provided for postural stabilization. In both situations voluntary movements are initiated by overcoming the reflexive signal. Meiry indicates that the disturbance to the eye tracking capability in the presence of motion (i.e., environmental fixation) is within a maximum of only ± 0.5° in the frequency range from .03 Hz to 2 Hz. Apparently this is well within the range of foveal vision and not sufficient to disturb visual acuity. However, it is evident from the eye traces presented by Meiry that a command signal from the motion receptors is received by the eye muscles driving the eye away from the fixated target which is later compensated by an eye movement to re-establish target fixation. This appears to be a rather regular phenomenon occurring at a fundamental frequency near 3 Hz. Meiry suggests that since the angular rotation of the eye prior to this return flick (fast phase nystagmus) appears to be random, the phenomenon is controlled by the central nervous system rather than position limiting in the eye.

3.3 MOTION SPECTRUM OF THE AIRCRAFT ENVIRONMENT

The next aspect of motion cueing which should be examined is the motion "environment" in which the pilot finds himself when he dons his new exoskeleton, the aircraft, in comparison to that which we have termed the natural environment. In what ways are these two environmental situations alike; how do they differ?

Of what does the motion environment consist? In essence, it consists of a panorama of forces and torques and their time histories as they act upon the various motion receptive organs of the human. The motion receptors have been discussed in Section 3.2. It is intuitively evident that such a panorama is immense and defies definition in the time sense. It is less pleonastically described statistically, in terms of its spectral density. For any specified force, the power spectrum describes the frequencies at which the largest concentration of power or action producing mechanisms occur. One must be careful to select the proper spectrum in terms of receptor characteristics for examination. For example, a receptor which transduces relative position may have a higher response sensitivity to a comparatively lower frequency component of a motion than a receptor which transduces acceleration. Where the highest energy levels are concentrated the more accurately these signals must be received in order to replicate the transmitted signals.

A search of the literature has failed to show any evidence of such a description of the acceleration environment in aircraft. Hixson and Niven (1968, 1969) have made numerous inflight recordings of the linear and angular accelerations at the pilot's station in various military helicopters during the various maneuvers. The vehicles include the AH-1G (Huey Cobra), UH-1B (Huey), OH-6A (Cayuse), CH-54 (Flying Crane), CH-47A (Chinook), and UH-2B (Seasprite). The data are illustrated as time recordings and it appears difficult to observe correlations in spectral signatures among the various aircraft maneuvers and airspeeds. To date no spectral summary data of these recordings have been published. There are data supplied by aircraft manufacturers which can be used to describe the response in various dimensions of aircraft to atmospheric disturbances such as gusts, clear air turbulence (CAT), thunderstorms, drafts in cumulus clouds, etc. Considerable effort has been expended in deriving statistical descriptions of atmospheric disturbances (Press, Meadows & Hadlock, 1956). A method for computing the spectral density of the response of the aircraft to this disturbance has been developed by Etkin (1959). Computing the forces and torques at the pilot's station as a function of the velocities and accelerations of the center of gravity of the aircraft, one can describe statistically the motion environment of the pilot due to aircraft response to turbulent air. From this one may derive the maximum angular and linear accelerations in any direction (i.e., pitch, heave, etc.) and also the "character" of the acceleration (i.e., its frequency makeup). In essence this presumes the pilot to be only a passenger in the aircraft since this spectrum does not include the movement of the aircraft in response to the pilot's movement of the controls, which is, in part, a response to the disturbing function.

The work done by McRuer, Graham, Krendel and Reisener (1965), which examines human pilot dynamics with a large variety of combinations of controlled elements and forcing functions can be regarded as an investigation of the environment created by the pilot in order to complete the given task (forcing function) with the given aircraft (controlled element). The authors have illustrated that the total environment tends to be constant. In their notation, Yp Yc is predictable and generally invariant in frequency ranges which govern closed loop system error. This work, however, does not include motion as an input to the pilot. Consequently we are left with merely a description of the visual environment with a fixed manipulator (i.e., one with invariant force/displacement dynamics) and fixed visual display. Magdaleno and McRuer (1966) illustrate the variation in environment produced by various manipulator load dynamics imposed upon the pilot. The variation produced by certain modes of motion in a ground based simulator was investigated by Stapleford, Peters and Alex (1969). This work apparently provides the closest description available to that of the in-flight, pilot induced motion environment. This motion environment represents only a facsimile of the one which we are seeking since the limited movement of the moving base of the simulator causes the motion to be adulterated. In essence, a description of the spectrum of the total pilot and gust induced in-flight motion environment was not evidenced by any research examined. Apparently many simulator manufacturers and customers use in their specifications data concerning maximum expected accelerations and velocities from examination of aircraft performance data and their experience with extant simulators.

An heuristic description of the aircraft motion spectrum includes contrasts and similarities with the "natural" environment. Since the aircraft was developed for control by the human operator (in contrast to a vehicle designed for flight without a human controller and/or passenger, such as a guided missile), one would expect that such a machine would contain characteristics which fit to a certain degree within the normal range of human experience. It should be kept in mind that this body machinery is highly adapted by natural selection to the environment in which it has evolved and the shortcomings of this machinery become apparent when we attempt to use it in a new environmental realm such as in flight.

There are many aspects of the flight situation which are so highly compatible in a motion perceptive sense with the "natural" motion realm, that we may lead ourselves astray in analyzing motion cueing in simulator experiments by unwittingly designing experiments in which motion cues in flight are more or less in tune with those in natural motion. Turbulent high speed - low altitude flight is analogous to running, in respect to resultant forces on the pilot except for the periodicity of the running stride. However, this periodicity may be injected voluntarily into the flight situation by the pilot as an active (i.e., energy producing) rather than as a strictly passive (following) component of the man-aircraft system. The only translation needed is the transformation of a reflexive limb muscle balancing response into an appropriate control response. Examination of the design of both control response direction and control feel indicates that these are consistent with the reflexive response of the limbs in postural control both in direction and appropriate muscle tension-relaxation relationships. A jet fighter aircraft (i.e., one with relatively rapid output response) being flown VFR in a pursuit course with rapid, relatively small deviations in roll and pitch represents the closest analogy in flight to that which we have termed the natural environment. The relationship, in a motion sense, to the running situation is easy to draw. As a consequence one would expect under these circumstances that the motion sensing apparatus of the human pilot can be utilized to its most full advantage. Even though the limb response must be relearned in order to manipulate the controller the reflexive response is fully operational. If, however, the entire motion sensing apparatus is to be used to its full advantage, all input information to which it can response should be supplied. Generally, the frequency content of the aircraft pitch response, for example, is upper band limited below the capability of the eye tracking compensation frequency

(2.5 Hz) and some phases of the direct motion sensory receptive system. It is hypothesized that what the pilot would attempt to do is to actively supply these missing upper frequencies. This type of input in part describes what has been termed the pilot remnant.

The remnant is that portion of the pilot's output which is not linearly correlated with the forcing function. In other words, this portion of the pilot's response was not demanded by reaction to the system behavior directly. At frequencies in the range of 1.0 Hz the pilot may be acting analogously to an adaptive control system which operates in a limit cycle. In such a system small high frequency pulses are used to disturb the system and identify the system response to those pulses. The response to the disturbing signal is used to adjust the control system parametric gains. Weir (1966) suggests that such a "dither adaptive" scheme enables the pilot to readapt his describing function within a very few seconds to some new controlled element function, perhaps produced due to a system failure. It becomes evident that system response in a simulator should be faithfully reproduced in the dither frequency range, if any accurate response information is to be obtained concerning the controlled system.

If the pilot is indeed dither adaptive, the question arises concerning the source of the feedback information concerning the controlled element. In control systems in which all feedback is visual, small perturbations in the visual scene give dither feedback information. Systems in which both vision and motion feedback are present lend themselves to adaptive feedback through the motion receptors since lower total movement at higher frequencies are necessary to impart feedback signals to the operator. Systems in which cues to system state may be received through control movement feedback are postulated to be most informative to dither adaptive behavior patterns. Control movement cueing is discussed in Chapter 4.0.

In addition to the movement which the pilot induces intentionally into the aircraft in order to produce the necessary high frequency information, there are resultant movements of the aircraft due either to pilot inputs or to external disturbances which characteristically contain high energy components of movement at frequencies less than the natural environmental spectrum. For example, a side force would call for a reflexive response of extension of a supporting limb in the direction of the side force. This is also the appropriate response called for in the aircraft control design, i.e., to push the rudder in the direction of the side force. Normally such a force would be of relatively short duration. Any prolonged steady state force in the aircraft environment must be interpreted by the pilot through the CNS by integration with the visual information to produce a correct interpretation of the aircraft situation. This is the technique presently in use in moving base simulators, i.e., using the gravity vector to simulate a side force by rolling the simulator to the appropriate side and depending upon the dominance of a strong visual cue contradicting the angular proprioception of roll and enhancing the linear acceleration proprioception due to gravity to produce the percept of side slip or skid. Whether or not such a technique is effective depends upon the dominance of the visual perception over the motion percept. This dominance is dependent upon several factors: the supposition that the pilot is watching exactly what he is supposed to watch when the movement is initiated, the experience level of the pilot, and the secondary demands or stress upon him. The less trained and more stressed, the more likely he will revert to reflexive behavior (Peters, 1969).

There are many flight situations which contain frequencies lower than those of the natural motion spectrum. These movements in addition to those produced by purely visually derived phenomena such as autokinesis, are most likely the major contributors to spatial disorientation in flight.

It is a reasonable hypothesis that these in-flight illusions are due to stimulation of the motion receptors in the unnatural (to man) three dimensional realm of flight. Peters (1969) has made a comprehensive examination of the relation of the vestibular system to (1) the illusory perception of motion, and (2) the visual illusions created by the effect of the motion receptors upon the oculomotor reflex system. The former group involve such phenomena as sensations of climbing in a turn, diving when recovering from a turn, opposite tilt in a skid, nose-high attitude during take off, nose down attitude during deceleration, nose high attitude or inversion during pushover from a climb to level flight, the leans, misestimate of degree of bank, graveyard spiral, graveyard spin and Coriolis illusion. The latter group include the oculogravic, elevator, oculogyral and Coriolis illusions. All of these phenomena are represented in in-flight occurrences due to the fact that the motion receptors of man are not matched to the portion of the flight environment in which these phenomena occur. They are disorienting, in the sense that the pilot experiences a false perception of attitude or motion, but may or may not produce the phenomena commonly termed vertigo depending upon the amount of information available from other sensory sources.

3.4 MOTION PARAMETERS IN MOVING BASE TRAINER DESIGN

The design of moving base trainers and software designs of driving functions to these trainers have a tremendous range. These vary from the centrifuge, which simulates effects ranging from zero to high "g" to small excursion, six degrees of freedom synergistic platforms. Obviously a wide variety of motion characteristics might be incorporated into a trainer depending upon the intended use of the device. Some of those characteristics felt to be important for consideration are discussed here.

3.4.1 Uncorrelated Motion "Breakloose" Phenomenon

Early in the development of moving base trainers, a motion phenomenon which can loosely be described as "breakloose" vibration was introduced. In such a device the movement of the simulator was completely uncorrelated with movement of controls or visual display.

The motion cues presented to the pilot by such a characteristic of the device may belong to the set of non-relevant, masking or conflicting cues depending upon the structure of the spectral density of the breakloose motion. The breakloose vibration should be characterized as a random motion the mean of which is zero and the spectrum of which consists exclusively of frequencies high with respect to those generated by the pilot or gust induced aircraft motion environment. Several factors discussed in Sections 3.2 and 3.3 should be considered in relation to breakloose vibration which is generally an attempt to create the realism cue of engine induced vibration of the aircraft structure and/or low intensity rough air. These include:

1. The unknown spectrum of the pilot induced aircraft motion environment.

2. The resonant frequencies of the human body.

The correlation of structurally transduced engine vibrations and logical noises is discussed in Chapter 5.0. If it is found that the engine sound/vibration phenomenon produces control or aircraft state cues, it is evident that the breakloose motion should be carefully structured so as not to produce erroneous information about the power plant.

The resonant frequencies of the human may be excited by the breakloose motion so that visual tracking may be disturbed. This resonance may also occur during buffet. An in-flight study of the effect of buffet frequencies (which are near 10 Hz) upon tracking precision in their fighter aircraft was made by Sisk (1970). In this study it was determined that the vibrational effect was primarily upon the pilot to aircraft displacement rather than upon the instrument to aircraft displacement. It has been mentioned in Section 3.2.1 that visual acuity is greatly disturbed at 11 Hz. There is the possibility that the instruments may be vibrated so that reading them is difficult. Breakloose can interfere with the ability of the pilot to produce accurate input movements, to receive input information kinesthetically, and to apply dither adaptive procedures.

Certainly if the frequency components of the breakloose vibration are low enough to cross into the pilot induced motion spectrum they may be interpreted as control cues through reflexive body responses. The uncorrelated nature of the random vibration will produce conflicting cues a large percentage of the time. Whether the pilot is able to suppress reflexive responses either posturally or in the oculomotor compensatory system is unknown, although preliminary analysis of results of an unpublished study using the Grumman Research Simulator (1969) indicate that performance improves with suppression of uncorrelated motion at frequencies greater than 3.5 Hz.

An additional and perhaps valuable attribute of breakloose vibratory motion is the capability for using it to mask erroneous cues produced by stiction in the simulator device mechanism or even to prevent such stiction.

3.4.2 Uncorrelated Motion and Illusions.

In Section 3.3 visual illusions created by motion receptors were discussed. These illusions can be evoked and have been studied in a centrifuge. According to Clark and Stewart (1967) judgments of attitude are influenced not only by stimulation of the vestibular system but are modulated by tactual and proprioceptive information. Coriolis illusions on the other hand appear to be independent of other sensory information. When these illusions occur, their influence on aircraft control can be significant. Certainly the training curriculum, whether in the simulator or in the aircraft, should include familiarization with the occurrence of these illusions, but it is not within the scope of this report to suggest investigative studies dealing with simulator training to increase ability to cope with the effect of these illusions upon performance.

The motions involved in eliciting illusory phenomena are very low frequency as are those motions which are involved in producing motion sickness. Physical movement of the individual is, of course, not necessary to produce motion sickness. This can be induced by movement of the visual scene with or without concurrent movement of the observer. The investigation of motion sickness is also beyond the study recommendations to be made here, although studies which have been made by Barrett and Thornton (1968) and Barrett, Thornton and Cabe (1970) indicate that the perceptual style (i.e., field dependence vs. field independence) of the individual is involved in the motion sickness phenomenon. Perceptual style may also be very influential in the response of individuals to variation in dynamic motion cues produced in simulators. Field dependency tests should be administered and correlated with motion variation experiments.

3.4.3 The Physical vs. the Perceptual Fidelity Approach to Correlated Motion in Design.

The trend in moving based simulation has swung from the early uncorrelated breakloose movement to a higher degree of physical fidelity of simulator movement with actual movement of the aircraft.

Physical fidelity implies the instantaneous correspondence in time of the linear and angular accelerations at the pilot's station in the moving base simulator with those linear and angular accelerations which would occur at the pilot's station in the actual aircraft which is being simulated. An attempt to produce physical fidelity has led to the conclusion that total ground based physical fidelity is impossible and some "point of diminishing returns" should be reached at which no additional benefits in motion cueing can be reaped by larger simulator excursions.

The "point of diminishing returns" approach also appears to be futile. This approach still looks toward the concept of physical fidelity rather than perceptual fidelity, which is the conceptual orientation of this report.

The dominance of unambiguous motion cueing in the higher frequency ranges of the spectrum would indicate that accurate duplication of movement of these frequencies would contribute the greatest information to the control strategy which must be learned in order to produce the greater transfer of training between the simulator and aircraft. Analysis of the postural cueing mechanism suggests the area in which perceptual fidelity should be equated to physical fidelity is in the frequency range in which postural cueing is significant and in the dimensions in which the postural cue is the strongest. Interestingly if one considers the discussion of the head rocking and neck tension in Section 3.2.1, the dimensions of aircraft motion which produce the largest postural cues are heave, pitch and roll! In order to produce these accelerations accurately in a ground based simulator even in the relatively high frequency ranges at least a small amount of lateral and fore-aft travel must be induced to compensate for the effect of gravity. It is also possible that slight displacements of the body without total motion of the simulator cab can produce the same cue phenomenon. A device such as the Dyna Seat should be examined as a possible adjunct to the total cab motion. This may also be a device which may prove useful in overcoming the erroneous cue produced by the necessity of "washing out" a cab displacement at frequencies which produce motion primary cueing or when visual cue dominance is not significantly strong to relegate motion cueing to secondary cue status.

3.5 SIMULATOR MOTION AS AN EXPERIMENTAL VARIABLE

When carrying out research on the effects of simulator motion it is necessary to be operationally specific about what is meant by the motion characteristics of a simulator platform or other motion cueing device and by what metric or measurement they are expressed and quantified. Once motion characteristics are specified in operational terms as they apply to the dynamic movement of a crew station, empirical relationships can be established between their variations and other parameters in the training situation. The operational definition of the characteristics of motion and their method of measurement are necessary prerequisites to research on basic cues and transfer of training.

The analysis of motion cues has been approached with the goal of postulating what cues the pilot has available to him in exercising control of his aircraft. Once these cues have been postulated, the question becomes one of creating those cues for him by whatever means are possible within the constraints of a ground based motion device. The requirements for motion are then dictated by the requirement to provide the stimuli which produce certain cues to the pilot rather than duplicate the motion characteristics of the aircraft per se.

Boundaries must be set about the population of motion characteristics to be examined. In this study consideration is limited to those characteristics which provide cues to operators of aircraft. Further, they are limited to those characteristics of military aircraft, both rotary and fixed wing, which the Navy uses for training and operations. Thus, in setting bounds upon the research to be carried out on simulator motion, only those aircraft in the Navy inventory and those categories of control outlined in Chapter 1.0 are considered.

In summary, descriptors of motion characteristics and methods of measurement are needed which will allow manipulation of motion as an independent variable in determining the effect of its variation upon pilot behavior. Further descriptions are needed which are useable by the simulator design engineer. To accomplish this the specification of the measures and procedures by which we determine the motion characteristics of a motion cueing device need to be made explicit.

3.5.1 Measurement of Motion Device Characteristics

When the goal is to determine the characteristics of any physical system, it is necessary to be explicit concerning the metrics used to describe the system and the procedures by which the values of these metrics are to be determined. A simulator platform is such a physical system. The discussion here refers to motion platforms and simulator motion devices (e.g., Dyna Seat) although for convenience, the term motion platform is used to denote all such devices. There are two distinct aspects to the description of the dynamic response characteristics of the simulator platform. The first involves a description of limits of linearity of the device; these are usually described in terms of maximum displacements, velocities and accelerations and commonly described in a system vibration nomograph. (See Figure 3.2). The second aspect is the response characteristics within these limits which can be approximately described by a linear differential equation. The solution of this differential equation consists of two parts:

1. The complementary function, which describes the transient portion of the response, and

2. The particular integral, which represents the steady state response.

A man, whose sensory receptors are being stimulated by the movement of the motion platform, perceives not only the steady state but the transient portion of that movement. Hence some metric which describes both transient and steady responses to a given input must be used. It should be noted the term steady state may or may not be a static state. It is equally valid to speak of the steady sinusoidal response as the steady state step or pulse response. Similarly one may refer to the transient response of a system to any of these three (or any other) inputs.

Performance criteria of physical systems have (until relatively recently with the development of optimal control theory) been expressed in terms of time constant, rise time, settling time, maximum overshoot, etc. in response to pulse or step inputs. These criteria are the easiest ones to "visualize," and to make assumptions about concerning their relative merits. For example, one may hypothesize that too long a time delay (i.e., time constant) between an input and the appearance of an output will be of negative benefit to a human operator of a system. Intuitively this appears to be a reasonable assumption. Again one may make judgments concerning the relative merits of the magnitude of the overshoot of a system response and magnitude of rise time of the same system. Unless it is possible to analyze a system in terms of optimization of specific

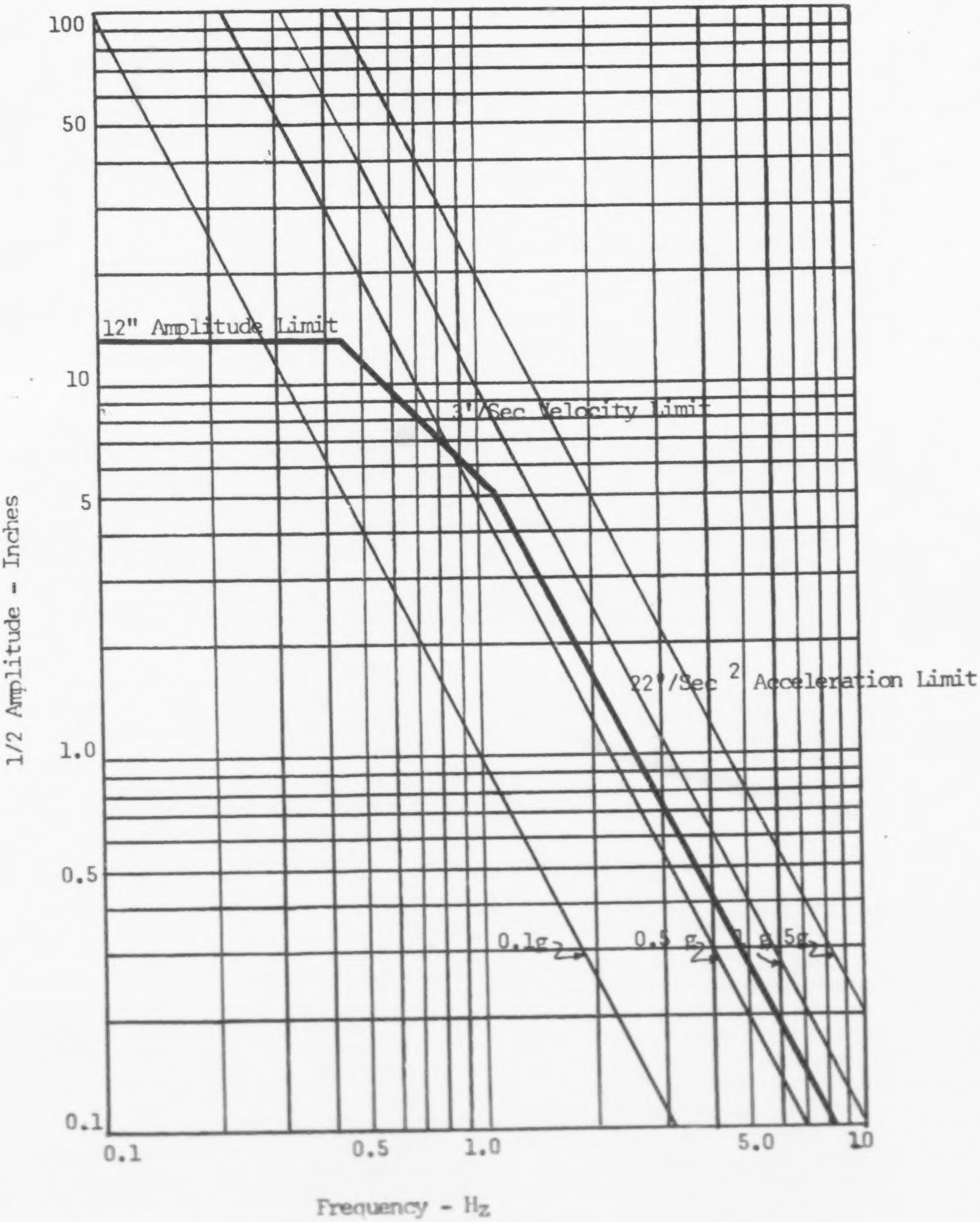

Figure 3.2 Vibration Nomograph
Showing Limits of Platform Motion

meaningful mission oriented criteria, these above mentioned performance qualities are fundamentally educated guesses.

It can be shown that the time response of a linear system to any known driving function uniquely determines its frequency response and conversely, if the frequency response of a system is known its time response to any specified driving function is uniquely determined.

Using this unique relationship between the time domain and frequency domain it becomes a matter of selecting the domain which offers the greatest ease of computation and manipulation. Generally speaking systematic analysis and synthesis procedures are more numerous in the frequency domain. Consequently, the frequency domain lends itself for selection as a metric for description of the motion platform characteristics.

When speaking of the variation of these characteristics in the frequency domain, it should be kept in mind that the ultimate concern is with the effects of these changes in the time domain. Since there is no a priori knowledge of the pilot's input, it is impossible to describe analytically the driving function to the motion platform so the specification of the response of the platform to any specific input will necessarily be rather arbitrary. When one describes the system characteristics in the frequency domain, he is in essence, placing a blanket specification on the system response to any driving function. When one alters system characteristics in the frequency domain, he varies such phenomena in the time domain as rate of onset of platform acceleration, platform acceleration, platform rate and platform position at any instance of time in comparison to the driving signal. It is possible then, to vary systematically the system characteristics and to determine the relation of this variation to pilot control behavior.

3.6 EXPERIMENTAL TESTING OF THE HYPOTHESES CONCERNING MOTION CUEING

3.6.1 Development of a Physical Model.

The discussion in Sections 3.2 and 3.3 concerned the postulating of certain principles (based upon physiologic and behavioral data from the literature) which constitute the elements and elemental interactions of a model of the human operators response to vehicle motions. It remains to develop the hypothetical mathematical relationships which govern the head-neck articulation and the resultant signals therefrom, based upon the postulates developed in the discussion in this Chapter. Processing of these signals to evoke reflexive postural response occurs most probably in the peripheral nervous system, as indicated in Figure 3-3, and additionally in the CNS. The modeling of the processes within the centers of the nervous systems shown in

Figure 3-3 remains to be accomplished. The development of this aspect of the model should add a great deal to our understanding of the sufficient as well as the necessary simulation of motion. Until such a model is developed, we must rely upon that portion of the total model about which some valid appearing conjectures can be made. Even a limited model will give insight into the critical experiments to be conducted in order to validate, modify, or extend the model.

The derivation of the equations which express the inertia, viscosity and springiness of the articulated portions of the body, which act as motion sensors, becomes the fundamental task. Recalling the discussion in Section 3.2, in which the various portions of the body were described as being analogous to sections of a harmonic analyzer, it should be kept in mind that the signature of the signal (i.e., engine vibration, aircraft response to control movement, etc.) to be conveyed to the operator should dictate the area of the body with which the mathematical analysis should be concerned. For example, it may be necessary to transmit engine "buzz" only to the limbs rather than to attempt to move an entire simulator platform. Once the equations of motion are derived, the numerical values of the parameters which comprise them must be determined. Although mass and inertia remain constant, voluntary control of muscle tension causes considerable variation in both elasticity and viscosity (Agarwahl, et al., 1969). The range of elasticity particularly will vary the bandwidth of sensitivity since frequency is directly proportional to stiffness. This model then will give the approximate frequency bandwidth to which various portions of the motion sensory system are sensitive.

3.6.2 Measurement of the Aircraft Acceleration Environment

More information concerning the in-flight acceleration environment must be obtained in order to complete the sensor - input block in the motion perception picture. A partial description of motion information can be gleaned from data which describe the three linear and three angular accelerations at some point near the pilot's station. These in-flight data may be used with the receptor-interaction model described in Section 3.6.1 to develop an hypothetical input to the nervous system. A more desirable set of data would include measures of the forces acting upon the various component parts of the motion sensory system. For example, observations of automobile drivers can be made in which the operator will align his head so that the eye line remains parallel to the horizon even if the vehicle does not. In this case a set of accelerations measured along axes fixed to the vehicle is not indicative of the signals received by the vestibular system.

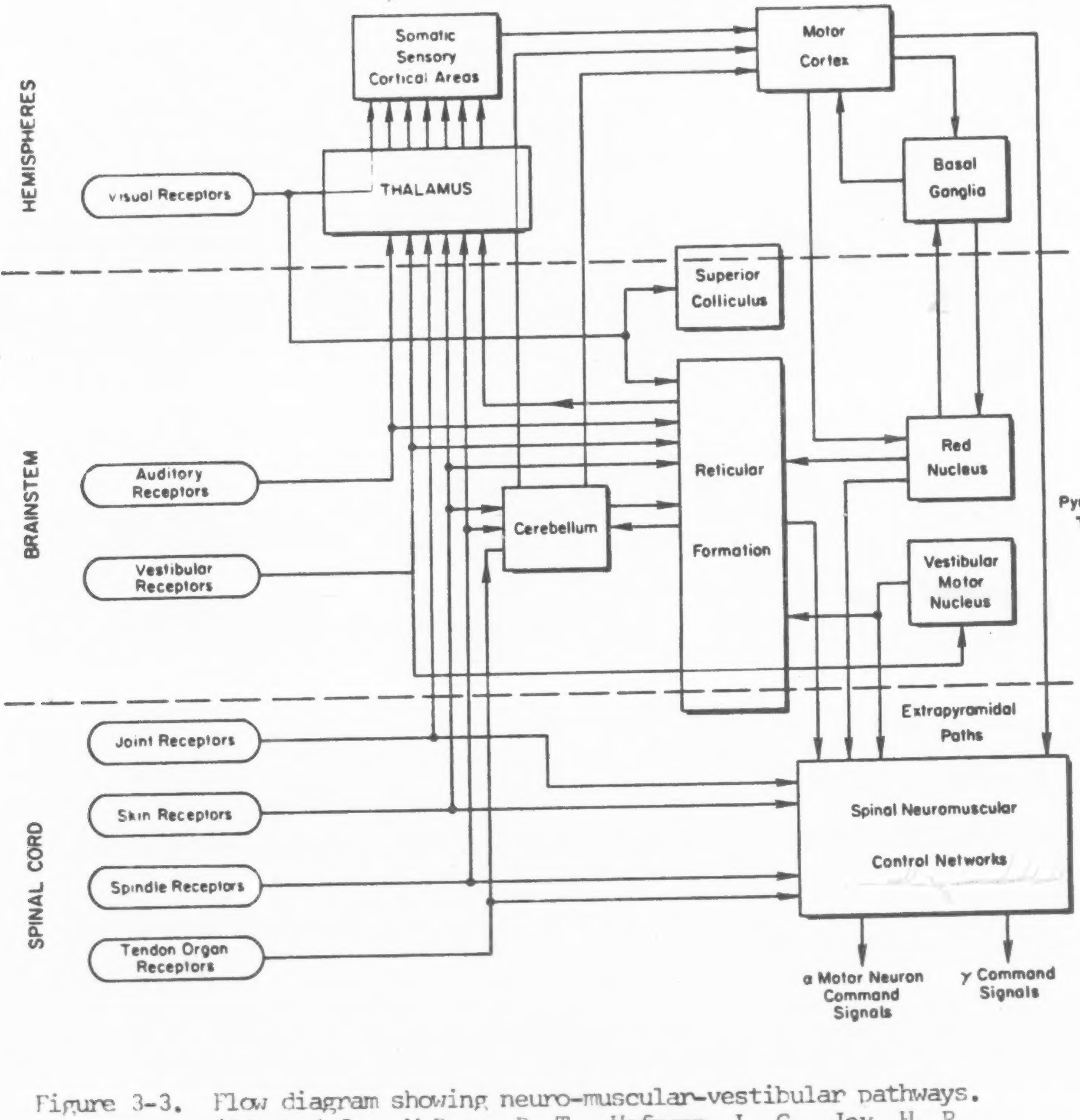
HEMISPHERES
BRAINSTEM
SPINAL CORD
Somatic Sensory Cortical Areas
Motor Cortex
Basal Ganglia
THALAMUS
Visual Receptors
Superior Colliculus
Reticular Formation
Red Nucleus
Auditory Receptors
Vestibular Receptors
Cerebellum
Vestibular Motor Nucleus
Pyramidal Tract
Extrapyramidal Paths
Joint Receptors
Skin Receptors
Spindle Receptors
Tendon Organ Receptors
Spinal Neuromuscular Control Networks
α Motor Neuron Command Signals
γ Command Signals

Figure 3-3. Flow diagram showing neuro-muscular-vestibular pathways. (Adopted from McRuer, D. T., Hofmann, L. G., Jex, H. R., Moore, G. P., Phatak, A. V., Weir, D. H., Wolkovitch, J. New Approaches to Human-Pilot/Vehicle Dynamic Analysis, Tech. Rpt. AFFDL-TR-67-150. Air Force Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, February 1968. AD 667 549)

The form in which these data are summarized is also of importance. It is recommended that the spectral density of forces as a function of frequency be the basis for the presentation of the in-flight data. Composite data by aircraft type and maneuver should be examined to determine the actual range of physical variation of motion information.

In addition, it would be useful to compare these data with an accurate determination of the spectral density of the natural movements of man. If these data include variations such as movement with and without the visual sense and movement of labyrinthine defective versus normal persons, an estimate of the contribution of visual and vestibular inputs can be made.

3.6.3 Testing the Model on Simulation Devices.

Assuming that the model described in Section 3.6.1 and the natural motion spectrum have been described as a function of frequency, it is possible to designate the bandwidth of the postural reflex system. It has been hypothesized in Section 3.2 that the unambiguous assessment of the motion environment is possible only when the postural reflex is invoked. It may be inferred from this that perceptual motion fidelity in this range requires physical motion fidelity. If this is so the effective bandwidth of the simulator may be adjusted initially to conform to the postural reflex bandwidth. The effective bandwidth of the simulator platform is a function of the electro-mechanical hardware as well as the computer software from which driving signals to the platform equipment are derived, as discussed in Section 3.5.1. Variation of the lower frequency cut-off of the motion spectrum in roll and lateral translation was the point of investigation by Stapleford et al. (1969). The upper cut off frequency remained constant in this study. In view of the hypotheses of this Chapter the upper frequency cut-off of the simulator used in Stapleford's study appears to be too low to allow postural reflex fidelity. With a gyro-horizon as the visual display Stapleford was able to increase the lower cut-off frequency to as high as 2.0 rad/sec without significant variation in performance. The effect of increased visual gain may be to increase the lower cut-off frequency beyond that possible with instrument displays. The interaction of the effect of the high frequency cut off and the bandwidth of the controller may also be the subject of simulator investigation using a similar experimental technique.

The development of a device similar to Dyna Seat which torques the trunk or other parts of the body in order to produce the desired response would be a valuable asset in testing further hypotheses. Such a device may be used to produce unbalancing forces on the body. The angular motion of the entire simulator platform may be combined with this device to test the postulate as set forth by Roberts (Section 3.2) that the semicircular canals add the equivalent of quickening to the closed loop system.

Unless the time sequencing of the interaction of control movement, muscle stretch, vestibular and visual cueing is established, it is not possible to assess the contribution which the vestibulo-ocular movement makes to the perception of motion. Investigation should be made into the question of whether movement of the eye induced by the labyrinth signals is principally a long term (i.e., low frequency) phenomenon. If so the relative motion produced by moving the pilot only and not the entire cockpit contributes only a minor error to the eye tracking capability and does not complicate the motion perception phenomenon.

4.0 CONTROL MOVEMENT CUES

A feature of ground based trainers which has only recently been given any degree of attention is that of the cues derived by the operator from the movements of his limbs as he actuates controls. These are the kinesthetic cues which are the subject of discussion in this Chapter. The importance to training of the degree to which these cues are reproduced in the trainer is virtually unknown. Little research bears on the problem of the use of these cues in vehicle control and has been directed toward the effect upon transfer of training. Also, there is no uniform dimension(s) along which the parameter of control "feel" can be measured. Matheny and Wilkerson (1965) in a review of the problem of control feel distinguished two types of feedback from the stick, i.e., pressure and displacement. However, the relationships between gradients in pressure or displacement and system output are not known in anything approaching a complete way. Data provided by Jenkins (1947) demonstrates a Weber function for discrimination of changes in pressure which is one small step along the way toward the acquisition of the needed information.

Recent studies by Herzog (1969) give evidence of the importance of the limb position cues to the operator in compensatory tracking control. Herzog's results show that the combination of force and position (displacement) cues resulted in better performance than force cues alone for the types of control systems investigated. He further found that variations in manipulation spring constant and in viscous friction had negligible effect upon tracking performance.

The importance of some information feedback to the operator that he has definitely made a control input into the system is important in that it allows him to differentiate among the cues he is receiving. For example, as the pilot flies his aircraft in moderately rough air, feedback from his control inputs allows him to differentiate those movements of the aircraft which are due to his control inputs and those due to turbulence. Thus, he is aided in the control of his aircraft. Similarly, when using visual displays for compensatory training, the knowledge of his control inputs allows the pilot to differentiate those responses of the system due to his control input and those due to external forcing functions.

It is also important that we recognize that significant interactions may obtain among parameters of the control. For example, Muckler and Matheny (1954) found no differences in time to reach criterion proficiency on a transfer task when control coulomb friction was varied as an experimental variable in the training task. Nor did they find differences when control direction was reversed. However, when the interaction of these was studied a quite marked decrease in performance was observed.

The work of Matheny and Wilbanks under the Army/Navy Instrumentation Program (ANIP) in 1959 is directly relevant to the problem of control. Research under this program was divided into the two areas of (1) function integration, and (2) information feedback. Under function integration the concern was with the analysis of the functions to be controlled, their disposition and assignment. With respect to training devices it goes without saying that functions as assigned and integrated in the actual aircraft would be replicated in the training device. Information feedback was defined as the kinesthetic feedback of information derived for having moved the control by limb. Two prime considerations were felt to be important: (1) information coming from two or more sense modalities must not provide conflicting information and (2) where possible, information from one sense modality may be used to supplement information received by another. Thus, the information received by the operator as a function of the extent of displacement or amount of pressure introduced into a control could serve as a source of information to him for determining the present or predicted state of the vehicle.

Experiments carried out under the ANIP program having to do with feedback from controls are important to training in one respect. In these experiments both pressure and displacement controls were used with the same experimental equipment in which variation in lags in control display ratios as well as two different system transfer functions could be introduced. The system transfer functions were (1) a positively accelerated function and (2) a negatively accelerated function. The positively accelerated function acted as an unstable system with the negatively accelerated function acting as a stable system. One of the interesting results of the experiment was that the displacement control appeared to be superior to the pressure control for systems with lags above 0.3 seconds when the control-display ratio was constant. This finding held for both the stable and the unstable systems. The projection of these results to the requirements for trainers means that it may be important that pressure feedback not be inadvertently introduced into the control system of the trainer when the prime feedback source in the aircraft is displacement. The Matheny and Wilbanks data would indicate that the cut-off frequency of the system may be important in this respect.

The first order of business in the study of the kinesthetic feedback from control manipulanda is the development of a construct by which the characteristics of the device may be measured and systematically varied as an independent experimental variable. The construct which we recommend to be intensively investigated is that of the Effective Time Constant of the control. The basic concept of this constant is identical to that discussed in Section 1.4. The concept has been discussed fully by Matheny and Wilkerson (1965), by Matheny (1967), and Matheny (1969) and is based on the simple notion that effectiveness of operator control in a closed loop system is a function of the rapidity with which the operator receives feedback of the result of his control movement. The effective time constant for the visual sense may be determined for each dimension of control from knowledge of certain machine characteristics and the operator's threshold for perception of the machine output. A similar analysis can be made of the control manipulanda. Such an analysis is in need of development in the study of the cues presented to the operator by the control being manipulated and in the study of the interactive effect with other sensory cues.

5.0 AUDITORY CUES

5.1 INTRODUCTION

The previous sections of this report have used the information array approach as an analytic basis for the postulation of cues used in aircraft control and recommendations for needed research. This Chapter will deal with auditory cues and use as an analytic basis the stimulus-environment approach, as described in Chapter 1. The reasons for choosing this approach will be developed in this Chapter and are centered in our impression that the information available for the postulation of auditory cues in aircraft control is suggestive but incomplete. Therefore, even though it may be possible to postulate auditory cues with an information array approach, certain information is lacking which must be obtained using the stimulus-environment approach. In addition, special considerations in the identification and quantification of aural cues are discussed along with recomended alternatives which lead to the postulation of aural cues for aircraft control and their presentation in a simulator.

5.2 SOUND USED AS INFORMATION FOR CONTROL

There is anecdotal evidence that pilots use sounds as cues for control. The literature lends support to the notion that this is the case.

First, there are many examples of the use of auditory-type display information for the control of the aircraft. The outmoded aural radio range was once a primary means of radio navigation. Pilots were presented a Morse A or N when deviations to the right or left of a desired track occurred. Matheny and Wilkerson (1966) cite deFlorez's work in which he demonstrated that a pilot could fly an airplane with his eyes blindfolded when certain aircraft movements were encoded aurally. Other work cited by Matheny and Wilkerson (e.g., Forbes, 1946) verifies this. But, with the development of sophisticated navigation and display equipment, auditory signals were relegated to a secondary place as the navigational information was presented on a visual display. Vision thus became the primary sensory modality for control along and about the axes of the aircraft both during IFR and VFR flight.

Second, there is evidence that pilots can and do utilize the noise levels of reciprocating engine helicopters as a primary cue in the control of the engine rpm. This noise probably emanates from the engine, the exhaust, or a combination thereof. In single engine monoplanes noise levels have proven useful in the same manner. Engine rpm and propeller rpm can be controlled by making use of sounds. Other sounds such as the characteristic "whistle" or "sigh" have been used by pilots as a cue to an approaching stall.

Third, there is good indication that the auditory modality is quite useful as a warning signal detector and that peculiar noises are used for this purpose in the aircraft. Henneman (1954) reported that auditory stimuli tended to be inherently more attention demanding than visual stimuli of moderate intensity and that the ear was superior to vision for communicating warnings, commands, and status information to the operator.

It seemed reasonable, therefore, to postulate that there are aural cues which may be used in the control of an aircraft. However, we felt it desirable to distinguish inherent from man-made sounds. That is, the primary interest of this report was in whether the sounds are an integral part of the aircraft and as such could be correlated with aircraft control input, or whether the sounds are a part of a pre-programmed warning device presented over the intercommunications system of the aircraft. One would obviously concede that the latter would be an excellent auditory cue for control of the aircraft whereas the former requires more explanation.

5.3 CUES IN THE COCKPIT

5.3.1 The Cue Taxonomy

It was assumed that it is possible to identify relevant, primary auditory cues and that pilots can detect and use these cues for control. Such primary cues could be used as a means of providing information for the control of the aircraft or as a primary warning device. It was also assumed that auditory information could serve as relevant, complementary cues, enhancing and verifying information from other modalities and serving to add realism (in a simulator). Further, it was assumed that sounds can serve to mask relevant primary or secondary cues or conflict with complementary cues.

5.3.2 The Referent and Control Index

In Sections 1.3 of Chapter 1 two concepts were outlined: the referent and the control index. In considering aural cues for control the standard or referent may be considered to be stored internally, (i.e., in memory) while the control index would be the perceived sound which is to be compared with the referent. For example, the pilot would be presented with a particular sound and would compare this sound with his memory of the pitch or loudness level of the sound, adjusting the sound he perceives (the control index) with his stored referent.

5.3.3 Correlated vs. Uncorrelated Sounds

It is important in delineating cues in aircraft control that these cues be correlated with control input or state. Primarily, the specification of a sound as a cue implies that this cue is both detectable and useable by the pilot. A sound that cannot be correlated with a control input or state of the aircraft is, for all intents and purposes, useless to the pilot as an aid in control. Implicit in identification of a sound as correlated and useable as a cue to control is the idea that there are uncorrelated sounds also. Such a dichotomy seems to add confusion to the issue if the problem is approached along the lines that a sound which is not correlated with control input or state is uncorrelated and is merely background noise. Such may be the case, but in one sense background noise informs the pilot as to the state of the aircraft and, according to our operational definition this would be a correlated sound. The situation may be resolved by stating that, unless the pilot can and does associate the sound with a control input, state, or change of state of the aircraft it is for purposes of identification classified as uncorrelated. It may be convenient to think of uncorrelated sounds as serving mainly as background unless the sounds can be associated with some aspect of control, at which time they become correlated sounds. The important point is that any sound which can be correlated with some aspect of status or control can become a cue for control.

5.3.4 Sound Sources

The literature is sparse regarding information as to aural cues for control of aircraft. Perhaps the most complete exposition regarding sounds in aircraft environments is contained in the works of Hatfield and Gasaway (1963), Gasaway and Hatfield (1963), and Gasaway (1969). These authors have documented internal and external noise environments for each major type of Army aircraft during normal operations including ground operations, hover, normal and maximum cruise conditions. They discuss in detail the major contributions of noise generators in these environments and graphically present the data by octave-band analysis of intensities.

The works by Hatfield and Gasaway and Gasaway and Hatfield were done primarily as a contribution to aviation medicine, documenting the noise levels in aircraft in order that medical personnel would be aware of damage risks involved in flying. For this reason much of the data are less than optimal for the purpose of postulating cues. As an example, recordings are not made at the same location for all modes of flight, power setting, etc. for all aircraft. Consequently it is impossible to generalize with precision and, specifically, to derive the functional relationships that exist between control input and intensities at certain frequencies. Nevertheless, much useful information is contained in these volumes that is directly relevant and helpful.

Using the UH-1 series helicopter as an example, one sees that the different intensities inside the cockpit, when measured at the same location at different power settings, are a function of the flight profile. One sees a shift in the curves such that during ground operations the 37.5-75 Hz octave-band contains the most intense levels and during normal cruise the more intense noises are in the 75-150 Hz band. Such trends are, for the most part, common to all the aircraft sampled.

Perusal of the document by Gasaway and Hatfield shows that the preponderance of higher intensities are in those octave-bands below 1200 Hz. There are several implications which may be drawn for this, not the least of which is that loudness level may serve as an aural cue to control. Since the lower (below 1200 Hz) octave-bands contain the higher intensity levels this would mean that pilots could use loudness as a cue regardless of age. This is predicated on the work of Robinson and Dadson (1956) who found that equal-loudness relations with pure tones was independent of age at and below frequencies of 1 kHz. Further, Licklider (1951) cites evidence that at higher db levels and lower frequencies, smaller incremental changes in db are necessary to detect changes in intensity.

In the Gasaway and Hatfield studies there is evidence of frequency shifts as flight modes change. From this evidence we may also postulate that frequency is important and may serve as a cue in control. Again Licklider (1951) cites evidence to indicate that at intensities above 30 db and at frequencies below 1 kHz, changes of 3 Hz can be detected.

Because of the nature of the data cited, the generalizations that can be made are less than precise. Even though it appears at this point that pitch and loudness (the experiential sides of frequency and intensity) can be related to control as cues, additional recordings are called for so that they may be examined further. It is the necessity for these additional data which dictate the use of the stimulus-environment approach as the analytic basis in this portion of the investigation. Further, nothing has been said about the complexity of the waveform which the pilot is expected to analyze in extracting the cues. The stimulus-environment approach will aid in this respect and would, in addition, allow for verification of postulates as well as give needed information concerning frequency, intensity, waveform and spectral density. Collecting these data is viewed as an important step for several reasons.

If loudness is a cue for control the gaps must be filled because loudness is a function of the frequency, the intensity, and the bandwidth. Consequently verification of our postulates is contingent upon these three.

Bandwidth is important in its own right. For example, three bandwidths may have the same area in terms of sound intensity density spectra but may not be equally loud. These must be determined and correlated with control input or state of the aircraft in order to meet our criteria as a potential cue. Too, the width of the critical bands must be specifiable since this is a central part in the concept of masking.

Equally, pitch is more closely related to frequency but the relationship is not precisely linear. In order that we may be most specific, the relationships between the environmental variables of frequency, bandwidth, and intensity must be known and specifiable insofar as they affect the pilot.

The postulation of aural cues in control in terms of pitch and loudness raises the question of the operations of the ear in handling these inputs. It is beyond the scope of this report to deal with the problem in detail, but the point must be made that considerations as to whether the ear is primarily a frequency analyzer or can better be understood as an autocorrelator (Licklider, 1951) must be taken into account in the analysis of sounds for identification of possible cues.

It is evident from Gasaway's work that certain portions of a helicopter have characteristic frequencies which add to the total noise spectrum of the aircraft. It is not difficult to visualize the pilot as being able to determine components on the basis of pitch. It may be that the pilot is able to use both loudness and pitch at the lower frequencies, particularly at higher intensity levels, as cues in control, while he may use changes in frequency at the higher frequency levels. It is such postulates as these which may be generated through analysis of the sound data.

5.3.5 Masking

As indicated above, the bandwidth is critical as a factor in masking. The closer the two bandwidths are the more one will mask the other.

As was evident in searching the literature, much of the information in audition is in terms of pure tone research. Nonetheless, with pure tones, low frequency tones are more effective in masking high frequency tones whereas with the masking of pure tones with white noise it was found that masking was less critically a function of the frequency of the masked tone than with the pure tones (Licklider, 1951).

The relationship seems to be much less complicated insofar as intensity is concerned. We find, for example, that, no matter what the frequency of the masked tone, masking increases as the noise becomes more intense (Licklider, 1951).

Thus, both the frequency and the intensity of sounds appear to mask other sounds by raising the threshold or in some other way making it impossible to separate the tonal stimulation into components and thence discriminate the presence or absence of a tone. This is critically related to our postulations regarding the cues of pitch and loudness, particularly at the lower frequencies and higher intensities encountered in the cockpit environment of aircraft. Thus, sounds would mask cues in the same modality, as described above. The masking of cues in other modalities would probably take the form of conflicting with incoming information by drawing attention from that information to some sound component.

5.3.6 Contingencies

There are several factors which bear directly on the problem of whether a pilot can detect and discriminate pitch and loudness levels of sounds in the cockpit environment; namely the auditory apparatus, the nature of the equipment, and the type aircraft.

The ability of the pilot to make detections and discriminations is certainly dependent upon the state of his auditory apparatus. Surveys have shown that helicopter pilots are losing these abilities in the upper frequencies at an alarming rate. In dealing with this problem, Camp (1966, 1967, 1969) has done a considerable amount of work in recording noise environments of Army aircraft in order to improve attenuation characteristics of helmets and improve speech intelligibility. Thus, an improved helmet, in terms of attenuation characteristics, will probably reduce for a time the detectability of loudness levels by the pilot. However, it may be that signal detection will improve (Hatfield and Gasaway, 1963), and that the pilot can adapt to the attenuation characteristics and still be able to detect important cues.

Finally, as Gasaway and Hatfield (1963) pointed out, different aircraft will have different noise environments, making the detection and discrimination contingent upon the type aircraft.

5.4 RECOMMENDATIONS

In section 5.1 it was indicated that the stimulus-environment approach was deemed the more feasible approach to the investigation of aural cues in control. It should be evident at this point why it was felt that such was the case. To clarify the issue further one might look at the logical sequence in any research in which the investigator expects to make postulations and implement them. The normal sequence in such a case would be to make postulations based on empirical evidence (and perhaps calculated guesstimates) and take these postulates to the particular laboratory or field setting and set about to test them in an acceptable empirical way. This Chapter, on the other hand, has postulated certain cues and cue sources based on less than optimal information. In fact the data themselves recommend a more complete analysis of internal environments of the aircraft of interest in order to accept or reject or modify the postulates which have been made. Thus, the data are incomplete and would not allow for verification of the postulates. It is, therefore, essential to the verification process that the internal sound environment of the aircraft of interest to this study be recorded and analyzed using recordings at the pilot's station so that functional relationships between data and control input or aircraft state can be derived. This bears directly on the concepts that have been postulated with regard to predominance of certain frequency levels and the relationships of loudness level to frequency level, as outlined in this Chapter.

Analysis is particularly important for the synthesis of the sound in the simulator. For example, we have indicated that certain relationships exist in masking. In the event masking was deemed desirable in a simulator it would be important to know whether a high frequency or low frequency sound was to be masked. It may not be enough to merely introduce white noise in the simulator. These are some of the problems which require alleviation before sound synthesis is accomplished.

To this point synthesis and design of sound simulation have been based on subjective evaluation of electronically-produced sounds which may or may not represent the actual sound field. Table 1 represents the Research Tool Digital Computer System (RTDCS) concept of some of the sound effects and the required signals. This is a qualitative approach to the problem. In order to identify and quantify the information, again, we felt the stimulus-environment approach to be appropriate.

TABLE 1. SIGNALS PROVIDED BY RTDCS SOUND SIMULATION PROGRAM UNIT[1]

Sound Effect	Required Signals
Impeller Whine Generator Left Engine Right Engine	1. NL, RPM Left Engine 1. NR, RPM Right Engine
Crank Left Engine	1. NL 2. KL30IL, Flame
Right Engine	1. NR 2. KK30IR, Flame
Landing Gear Noises	1. VPI, Translational Velocity (0 - 250 knots)
Tire Rumble on Take-off and Landing Touch Down Impact, and Thump	1. VP, Translational Velocity 2. In Air
Tire Braking Screech Left and Right	1. VP, Translational Velocity 2. In Air
After Burner Noise Left Engine Right Engine	1. KK302L, A/B Left Engine 2. KK302R, A/B Right Engine
Air Noise	1. VP, Translational Velocity

[1] Adopted from NAVTRADEVCEN Technical Report 67-C-0196-7, January, 1969.

When cues and sources are considered in terms of application to the simulator a second problem must be considered. There are extraneous sounds correlated with the operation of the simulator platform which do not correlate with control of the aircraft simulated. These can mask relevant cues also. Masking platform-correlated cues with white noise is not desirable because of the possible interactions this noise may have with the relevant and non-relevant cues correlated with the simulated aircraft. Therefore, special consideration is required in that the platform must be suitably isolated such that extraneous noises associated with its operation do not interfere with the presentation of cues for control.

Since it is possible to present correlated cues for control only in a qualitative sense it is recommended that further work be undertaken in order that the cues may be more quantifiably specified so that their use may be facilitated. There are, of course, considerations for such an undertaking. Obviously, subjects should have hearing ability documented so that adequate relationships may be inferred on the basis of control cue sounds and hearing abilities. Too, any experimental evidence gathered in a laboratory setting which is not representative of the pilot's control task may produce misleading or incorrect data. Assuming, therefore, accepted laboratory procedures, this report suggests alternatives that could be followed in order that analysis and synthesis of aural cues for control might be accomplished.

Generally, high quality recordings of the sound fields at the pilot's station should be made in conjunction with changes in appropriate relevant control parameters. Detailed statistical analyses of these recordings is necessary in terms of spectral densities, harmonics, and correlations with the control parameters. Then the synthesis of the acoustic environment by electronic means suitably controllable by a digital computer could be accomplished, and various combinations of synthesized signals could be presented to experienced pilots for evaluation of the relative effect of particular components of the acoustic field.

An alternative procedure for processing the acoustic signals would be to pre-process the recorded signals by an analog real-time spectral analyzer and, with appropriate interface equipment, handle the majority of the other processing by digital computation. The advantages of the digital computer in accuracy, ease of storage, and retrieval of data as well as the increased flexibility in output formats and ease of program modification bias the analysis in its favor. The hybrid package may produce results more quickly than either analog or digital systems alone.

With regard to sound presentation, a method of presenting audio signals can be formulated without the use of electronic oscillators and attenuators. The recorded signals, after having been analyzed, could be stored and brought into an audio buffer as a function of the phase of flight being simulated. The buffer would serve two purposes. First, it would hold a given length signal and second, it would allow modification as a function of system status. A double-buffering technique could be employed to stay ahead of the system dynamics if necessary. This approach would have to be analyzed in regard to modification of the audio spectrum with changing system dynamics but the relatively unchanging nature of the sound spectrum due to maintaining the aircraft in fixed states over periods of time may prove it to be a feasible approach.

Figure 5.1 represents a flow chart diagram of a proposed data collection and analysis system. An advantage would be independence of fixed electronics and variability (by program change) of the sound spectrum.

In the current RTDCS system outlined previously the sounds that can be generated are limited to the simple functions of rpm and the electronic oscillators and attenuators external to the computer. Such a system lacks the flexibility necessary for research on the auditory cue problem.

If an adaptive system is desired (i.e., presentation of various component frequencies of the total sound spectrum with changes based on level of controllability) then an all-electric sound system such as the RTDCS becomes too restrictive in an experimental system. Regardless of mode of presentation, the analysis and synthesis of the audio spectrum are prerequisites to the design of an aural cue presentation system in the simulator.

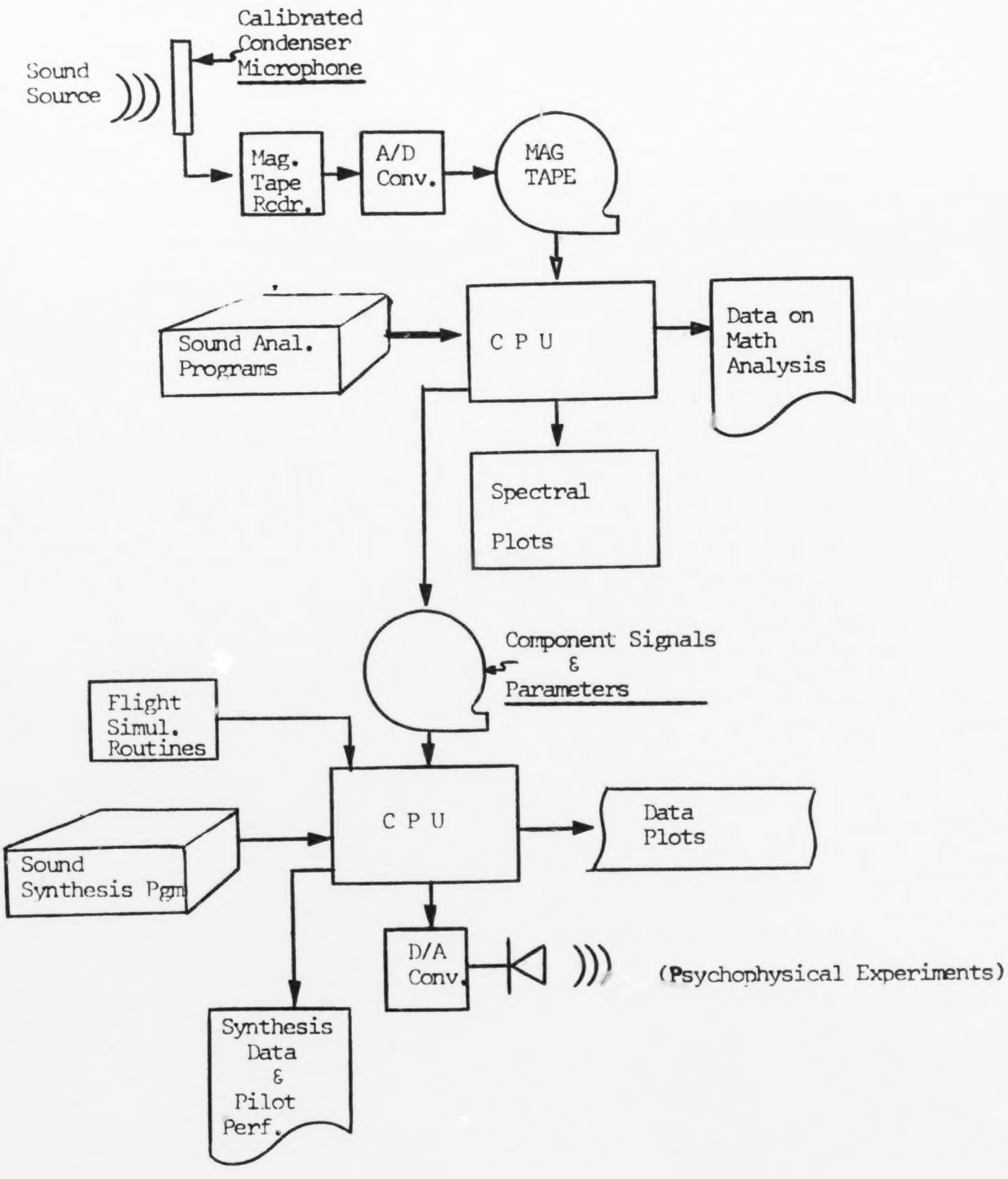
Calibrated
Condenser
Microphone
Sound
Source
Mag.
Tape
Rcdr.
A/D
Conv.
MAG
TAPE
Sound Anal.
Programs
C P U
Data on
Math
Analysis
Spectral
Plots
Component Signals
&
Parameters
Flight
Simul.
Routines
C P U
Data
Plots
Sound
Synthesis Pgm
D/A
Conv.
(Psychophysical Experiments)
Synthesis
Data
&
Pilot
Perf.

Figure 5.1. A Proposed Data Collection and Analysis Technique.

6.0 INTERACTIONS AMONG CUES

The essence and the complexity of the problem of the necessary cues to be incorporated into a ground based trainer centers about the interactions among the cues. That is, that the utility or non-utility, importance or non-importance of a cue in one sense modality may be and usually is contingent or dependent upon the cues being received by another. This section attempts to enumerate and to describe some of those interactions or contingencies which are felt to be particularly important with respect to training devices.

6.1 VISUAL AND MOTION INTERACTION

Many of the salient points with respect to the interaction between visual and motion cues have been presented in Chapters 2.0 and 3.0, Visual Cues and Motion Cues respectively. Specific interactive effects deemed of particular importance are discussed here.

6.1.1 Dominance of Cues

Both the in-flight and the moving base simulator environment are such that the total perception of motion generated by each is, in general, an ambiguous background of information. Unambiguous motion cues emerge from this background through addition of information from other sensory sources such as vision. In an aircraft maneuvering in such a manner so that the gravito-inertial vector is oriented approximately normal to the pilot, the motion perception is the same as if the pilot were flying straight and level. The interaction of this motion perception with visual cues provides the correct orientation information. The additional information from the visual scene is needed since the motion receptors are not adapted to movement in the larger three dimensional space in which aircraft maneuver. It is obvious that the visual scene must be clearly definitive and quite dominant in order to overcome a motion perception which, in a natural environment, would convey to the human that he is stationary and seated upright with respect to the ground.

The occurrence of vertigo in IFR flight is a common enough illustration of lack of visual dominance. The display on a gyro horizon is seldom a sufficiently compelling cue to prevent the interactions of the motion perception with other visual phenomena such as peripheral cloud particle flow or banked cloud layers. The factors which may cause cues in a visual scene to exert dominance over motion cues have been cited in Chapter 2.0. This dominance of the visual scene results in the primary cue being derived from the visual sense, relegating to the proprioceptive sense the provision of the complementary cue. The motion perception is not always ambiguous, however. As mentioned in Chapter 4.0, in those maneuvers or in certain phases of maneuvers where the correlation between natural and aircraft motion environment is high, the motion cues become primary and the visual cues complementary (if it is present) or conflicting (if absent or out of phase).

6.1.2 Gain of the Visual Display and Motion Cues

The essence of this problem lies in the fact that, when the operator and his vehicle move in space, it is the characteristics of the movement, i.e., its frequency or amplitude, which determine whether or not the operator will sense the movement first through his motion or his visual senses. For movements of the aircraft around the aircraft axes, i.e., attitudinal changes, motions are such that they will be sensed first through the motion senses. The visual senses are relied upon to corroborate or to substantiate the information received by the motion senses. Thus, the more qualitative aspects of the visual scene may be important when the interaction with the motion senses are considered. In some systems the rate of movement is such that the visual senses are able to detect the fact of movement before the motion senses. Such a slow moving system may be envisioned as the gradual drift of a spacecraft. Or the aircraft system may gradually drift into a bank or pitch below the threshold for motion perception with the first cue to the deviation being to the visual sense. Thus, the dynamics response of the system is an underlying parameter influencing the interaction between visual and motion cues. It may be hypothesized that the trainer required for transitioning experienced pilots to instrument flying of large aircraft could be entirely effective without motion due to the low rates of movement involved. On the other hand, training for low altitude high speed flight in which the pilot may be controlling a much lighter aircraft as a weapons platform may be hypothesized to require the lead information provided by the motion cues and thus require motion in the trainer for effective training. An examination of the difference between time to rise above threshold for the different sense modalities is important to the understanding of the interactions of cues.

6.1.3 Platform Motion and Color in the Visual Display

In the discussion of the variable of color as a visual cue it was postulated that it was not considered to be of high value as a primary relevant cue to control of the vehicle. It was stated, however, that it could exert an indirect effect through enhancing contrast or increasing the acceptability of the device to the trainee.

In the discussion of the interaction of motion with visual cues it was indicated that the interpretation of the motion cues are dependent for their interpretation upon supporting or complementary visual cues. This complementary nature (or conflicting nature) of the visual cue is important to the motion cue interpretation. It is postulated, therefore, that the variable of color in the visual display performs a supporting or complementary role to motion cues provided the colors are such as to enhance the acceptability of the visual display to the trainee.

6.2 CONTROL MOVEMENT AND MOTION CUE INTERACTION

The problem of the interaction between the control movement and motion cues was touched upon in Chapter 3.0. In that chapter it was stated that the cues of concern here, i.e., the feedback through the muscle senses from moving a control, act as a feed forward or quickening loop to provide information to the trainee of the action of the vehicle. That is to say that the feedback through the kinesthetic senses as a result of control motion allows the operator of a closed loop vehicle system to "sort out" the motion cues he receives which are due to his inputs into the machine and those which are due to external forcing functions. To the extent that the trainee comes to depend upon these kinesthetic cues and to learn to discriminate their characteristics, perceptual discrepancies between the trainer and the actual system to which he will transfer may act to create negative transfer. That is to say he comes to depend upon his kinesthetic feedback as information relevant and necessary to precise control.

The information received through the proprioceptive mechanisms of the arm may be dependent upon the force-displacement ratio in the manipulator, the damping and inertia of the manipulator, the degree of learning of the controlled element response to manipulator force or position output, as well as the degree of feedback information present in the manipulator force (and/or position) concerning the controlled element response. This last factor is the cue mechanized by bobweight feedback to the aircraft longitudinal control stick. In this case the pilot is presented with information concerning aircraft movement through the control stick by means of the effects of gravity and aircraft accelerations upon the bobweight resultant pull on the stick. It is hypothesized that the general effect of the bobweight feedback is to provide lead information to the pilot in a manner similar to that provided by postural and labyrinthine information. The frequencies at which lead is provided by bobweight feedback is a function of the system design parameters. The relationship of this frequency range of information compared to that provided by control stick dynamics is not known. Neither is the contribution of control stick dynamics to controlled element/pilot dynamics, Yp Yc (See Chapter 3.0). The experiments carried out by Herzog (1969) appear to indicate that stick dynamics matched to controlled element dynamics raise the Yp Yc crossover frequency considerably higher than proprioceptive information. This would lead one to infer that the information provided by control stick dynamics is considerably in advance of other cue sources.

6.3 CONTROL MOVEMENT FEEDBACK AND VISUAL CUES

The argument with respect to the interaction between kinesthetic and visual cues is exactly the same as that presented in Section 6.2 with respect to the interaction of kinesthetic and motion cues. That is to say that the kinesthetic feedback operates to provide the operator with advance information as to the results of his inputs as well as to allow him to sort out the result of his inputs from external forcing function inputs to the system. In the case of visual displays this sorting out of operator inputs from those of the external forcing functions is particularly relevant when the task of the operator is one of compensatory closed loop control.

7.0 PERFORMANCE MEASUREMENT AND EXPERIMENTATION

7.1 GENERAL DISCUSSION

The question to which a final answer is sought by these investigations is the relationship between the degree of incorporation of cues into the ground based trainer and the amount of transfer to the actual system. To carry out such experiments the classical savings in training time paradigm described in Gagne, Foster and Crowley (1948) could be used. The use of this experimental paradigm requires two groups of trainees, one of which receives training in the simulator and transfers to the aircraft while the other receives training in the aircraft only. An examination of the problem soon reveals, however, that transfer of training experiments in which operational or training aircraft are involved are difficult, time consuming and expensive. The fact of their interference with ongoing training programs or at least with ongoing trainees presents difficulties which are formidable.

It is recommended here that transfer of training experiments in the major areas discussed in this report be prefaced by other experimentation. These experiments are felt to be necessarily antecedent to transfer experiments in order that the experimental variables may be defined explicitly and meaningfully. The results of this preliminary experimentation may be used in two ways, either to specify variables in transfer experiments or, depending upon the assumptions one wishes to make, as data upon which to base simulator specifications. The basis for recommending this preliminary experimentation is set forth in the following discussion.

The point has been made by Matheny (1968) and others that the basis for a simulator specification should not be that it represents the physical characteristics of the aircraft system it simulates. Rather, its specifications should be based upon characteristics of the real aircraft which are perceptible to the pilot. That is to say that the simulator should incorporate perceptual or psychological realism rather than physical realism. This argument has been extended to say that it is pointless to build into the simulator characteristics which cannot be perceived or discriminated by the operator. It has also included the postulation that perceptual realism in the simulator can be created by physical characteristics other than those which bring about perceptual realism in the aircraft.

The central problem in simulator specification is the determination of what perceptual characteristics to build into the simulator in order to maximize its effectiveness for transfer of training to the actual aircraft. This would suggest that transfer of training studies are in order. However, we recommend that there is a necessary first step before transfer of training experiments are conducted.

This step is that of determining what physical characteristics produce perceptual discriminations (cues) in the context of piloting an aircraft. For example, the question may be raised as to what characteristics of the motion of an aircraft are perceptible to the pilot and are influential in his control of that system. The specification of the measurable characteristic of motion which is perceptible and related to pilot control behavior is required to be determined before transfer of training experiments can be economically undertaken. This first step, i.e., determining the physical parameter which underlies and gives rise to perceptual discriminations and control behavior, serves to set the limits on the physical parameters and to provide the experimental variables for transfer of training experiments. Once the quantifiable physical parameters of the simulator which provide the perceptual cues are known, transfer of training experimentation may be initiated to determine the effect of their inclusion and/or variation upon transfer of training.

Once the relationship between physical, quantitative parameters and perceptual behavior has been mapped out, the assumption could be made that the effectiveness of a training device is a function of the degree to which it incorporates those physical characteristics giving rise to these perceptual cues. However, it must be emphasized that the assumption relating degree of incorporation of cues to degree of transfer of training has not been empirically established. This is the function of transfer of training experiments.

To recapitulate, the first and necessary step is to determine what physical and measurable parameters of simulators are related to perceptual and control behavior. That is, it is necessary to identify and describe the physical parameters, vary them and determine if they are indeed related to control behavior. It can then be said that those "cues" which give rise to pilot behavior, and, when changed or eliminated do change his behavior have been identified. Given this information and making the assumption that amount of transfer is directly related to degree of incorporation of cues, certain conclusions with respect to the configuration of an effective trainer may be reached. That is, design specifications may be based upon the information that certain characteristics provide certain cues to the pilot in the control of his vehicle. However, the empiricist will wish to take those physical characteristics which have been found to provide cues to control and determine experimentally how their variation in training device affects transfer of training. It is the transfer of training experimentation which is relatively much more expensive and difficult to do.

At first glance the difficulty and expense of carrying out transfer of training experiments seem almost prohibitive. Not a little of the difficulty centers around obtaining subjects from the training or operational commands for use in carrying out the research. Another is the support of high performance operational aircraft. There are possible **alternatives, however, to training in** a complex simulator such as the TRADEC and transfer to an operational aircraft of the F-4 type.

One alternative is to establish the simulator itself as the criterion or transfer aircraft. This would require obtaining detailed data recordings of aircraft system outputs (altitude, heading, roll rate, bank angles, etc.) and pilot inputs for a series of representative maneuvers in the operational aircraft. From these data the simulator could be configured so as to require the same pilot inputs in obtaining the same system outputs for these maneuvers. This configuration of the TRADEC would then be used as the transfer or "operational aircraft" to which transfer of training from experimental configurations is measured. Although the representativeness of the simulator as a transfer aircraft can be criticized on several grounds this alternative does offer certain advantages. Most importantly, differences between the training or experimental configuration of the simulator and the criterion configuration can be tightly and systematically controlled. Transfer effects are not confounded by other direct or interactive effects of differences between the simulator and the transfer aircraft. The "pure", so to speak, effects of changes in the simulator upon transfer can therefore be isolated.

As another alternative, genuine transfer of training experiments could be carried out much less expensively using either military or non-military subjects through simulating a smaller training aircraft which is less expensive to operate. This would require obtaining the pertinent aircraft data and appropriate modification of software and hardware in the simulator. For a serious long range program of research to determine the direct empirical relationships between simulator characteristics, training technology and transfer of training this approach has much to recommend it. It will be noted that it would be concerned with a lower experience level trainee rather than the transitioning experienced pilot.

7.2 PERFORMANCE MEASUREMENT

Appropriate measures of performance must be selected whether carrying out the recommended cue identifying research or transfer of training experiments. For cue identifying experiments it is recommended that performance be measured in two major areas. These are (1) system output and (2) operator output. By system output is meant the measurement of system parameters directly related to the performance of the pilot and the task he is doing. Examples of these are pitch rate, pitch angle, altitude and heading. Further, system output parameters of interest will be specific to the tasks being performed. For example, in the approach and landing task vertical and lateral deviations from the required track through space, i.e., deviations from the glide path and localizer, would be of direct interest with respect to measuring system output.

By operator output is meant the control movements which the pilot makes as inputs into the aircraft system in bringing about the desired outputs. The temporal and spatial patterning of the control inputs made in order to exercise appropriate closed loop control of the system are the phenomena of interest which require summarization. The frequency and amplitude characteristics of the control inputs would appear to be important ways in which control input patterns can vary in response to changed system characteristics. These characteristics may be summarized through use of power density spectra, auto-correlation or, more simply, RMS or standard deviation.

In transfer of training experiments interest is centered primarily upon system output although control input data may be important to the understanding of the results of the experiment. In the classical transfer of training experiment the trainee practices until he reaches some stated level of proficiency in controlling system output both in the simulator and the aircraft. Proficiency levels are set on such system output parameters as airspeed, altitude, etc. Transfer is measured in terms of time saved, or additional time necessary, in attaining proficiency in the aircraft after practice in the simulator. To the extent that control techniques learned in the simulator are the same as required (or can be quickly adapted to those required) in the aircraft positive transfer will occur. However, if the control techniques acquired in the simulator are inappropriate to the aircraft negative transfer may occur. Therefore, the recording and analysis of control input data, both in simulator and aircraft whenever possible, will greatly aid the understanding of the factors affecting transfer of training.

7.3 VISUAL CUE EXPERIMENTATION

In Chapter 2.0 dealing with visual cues, experiments were suggested using the tethered Jaycopter in which training under experimental visual conditions could be compared with training under the more realistic and representative actual conditions. Upon consideration of experimental apparatus availability and the relative importance of the several visual cue problems, it is recommended that a number of experiments can be carried out in this equipment which would yield useful data. These experiments fall into four major areas: (1), a comparison of performance under conditions of binocular and monocular cues for helicopter hovering, (2) the effect upon performance of the method of encoding of the relevant variables for control of the six degrees of freedom of the helicopter during hover, (3) a test of the Matheny and Thielges model which proposes to predict the precision of helicopter control as a function of the placement of internal and external referents, and (4) a test of the relative applicability of different geometrical descriptions of visual space.

7.3.1 Monocular Versus Binocular Experimentation

The Jaycopter offers the opportunity for conducting a true transfer of training experiment in which the trainee is trained under monocular conditions and then transferred to flight under binocular conditions. The dual control feature of this equipment will allow the student to be trained in a manner analogous to conventional helicopter training in which the instructor allows the student to master single and then combinations of dimensions of control. Further, the computer controlled autopilot feature which may be added to this equipment would make possible the study of the monocular vs. binocular cue problem over a range of vehicle dynamics.

As a first experiment it is recommended that a classical Gagne (1948) transfer of training paradigm be used in which the degree of transfer in terms of time saved is determined through the training of an experimental and control group. Since the hovering maneuver is one of the first in the training curriculum it should not necessarily be required that the subjects in the experiment be candidates for pilot training. It may be possible to obtain subjects from Training Center permanent personnel or draw from the basic trainee group of the Center. It is recommended that the standard Navy selection tests be given the subjects and only those used as subjects who would qualify for pilot training. It is also recommended that in all tests in which visual and motion cues are the subjects of inquiry that subjects be given the Rod-Frame Test or Embedded Figures Test to determine their visual field dependency or independency.

It will be necessary to conduct pre-tests or pilot studies to determine final performance criteria in the device. Criteria may be established as holding altitude and X-Y translational position within set limits. Transfer of training is then measured in terms of time to reach these criteria.

7.3.2 Experimentation with Respect to Encoding of Visual Cues

Appendix A lists visual cues which depend upon certain external referents in the pilot's field of view and certain internal referents which are an integral part of his vehicle. Experimentation concerned with the encoding of the external visual world so as to provide external referents is inextricably confounded with the test of the Matheny-Thielges model discussed in the next Section, 7.3.3. However, the major experimental variable, the encoding of the external world scene so as to provide the necessary and sufficient information for control of the vehicle is discussed here.

Appendix, A, suggests that cues may be enumerated in terms of their relevancy for various dimensions of control of the vehicle. That is to say that certain cues are relevant to control of pitch, others to control of roll, etc. The external world encodement which provides the relevant cue for control of pitch and roll is postulated to be an horizon line with a representation of the ground plane as being a secondary cue. X and Y position on this ground plane is dependent upon some identifiable point upon the ground plane as the external referent. Control of altitude or deviations along the Z axis may be postulated as being dependent upon the cue of change in retinal size of some object or, more precisely, change in the perceived distance between two objects positioned on a ground plane some distance from the observer which the pilot observes at a particular angle of regard.

With respect to the encodement of the ground plane and the horizon, work carried out under the Army-Navy Instrumentation Program indicated that a wide variety of encodings, when interpreted in a static display, provided the necessary and sufficient information for judgments of pitch and roll of the vehicle (Matheny & Hardt, 1959; Elam, Emery & Matheny, 1961). Experiments carried out in the motion-base simulator also indicated that a grid plane, i.e., the ground plane encoded by a series of grid lines, provided the necessary and sufficient cue for the pilot to maintain his pitch, roll and position in the X-Y plane.

Experiments carried out in the helicopter using a quite crude grid plane display also demonstrated that the pilot could carry out the task of hovering and maintaining of X-Y position quite well with a very limited grid line representation of the ground plane as his visual display. (Wilkerson & Matheny, 1961c). However, only one transfer of training experiment was carried out. In that experiment (Feddersen & Matheny, 1962) subjects were trained until they had reached an asymptotic level of performance since the object of the experiment was not primarily that of transfer of training and no control group was trained. The results are, therefore, not highly informative except that, under the conditions of the study, a high level of positive transfer appeared to take place. The Jaycopter offers the opportunity for carrying out transfer of training experiments using different encodings of the postulated visual cues for the six dimensions of control of the helicopter.

The encoding of those cues which will enable the pilot to make the judgments of the required accuracy with respect to altitude is a major problem which was not solved in the ANIP program. During tests of the grid line display in the actual helicopter (Wilkerson & Matheny, 1961c) altitude was encoded through use of a vertical scale display which gave accurate qualitative, i.e., precise but non-quantitative information. It was an analog of the real world only in the sense that a marker moved up and down in a slot and the correct altitude was attained when the marker was kept at a designated position in the slot. The encoding of the external referents so as to provide the relevant cues for altitude control, therefore, have not been determined in any precise way.

It should be pointed out that the study of color versus achromatic displays can be undertaken in the Jaycopter. It is necessary for both the encoding experiments and the color experiments that a surround be constructed around the Jaycopter such that the encoding of the relevant cues in the external world can be systematically and quantitatively varied.

7.3.3 Test of the Matheny-Thielges Model

The model developed by Matheny and Thielges for describing the cue structure for the pilot in hovering the helicopter has been described briefly in Chapter 2.0. It is described in detail in Matheny and Thielges (1965) and in Thielges and Matheny (1966). In brief, to develop the model an analysis was made in which the necessary and sufficient cues were postulated for maintaining control of the helicopter in its six degrees of freedom of pitch, roll, yaw, altitude, fore and aft, and lateral translation. A model was developed expressing the relationship between the cue sources in the external world and the information they provide for control by dimension of vehicle motion, i.e., pitch, roll, yaw, and X, Y, Z translation.

It was postulated that a critical parameter in describing these cues was the relationship between an internal referent on the vehicle itself and an external referent in the real world visual scene. The internal referent could be an index which was motionless relative to the aircraft such as a structural member of the aircraft. The external referent was defined as being a fixed point on the ground plane and/or horizon external to the vehicle. From the model, postulates can be derived predicting the precision of control of the vehicle as a function of the area in the visual scene at which the external and internal referents are located, the relationship or distance between the two referents, and the vehicle dimension of control being exercised. From the model are derived information density plots which identify those areas of the windscreen from which maximum information may be obtained by the pilot as a function of his dimension of control and placement of internal and external referents.

A test of the model using laboratory equipment and a modified psychophysical technique supported the validity of the model (Thielges, 1966). Predictions with respect to detection of deviations of the internal referent from the external referent as a function of the various parameters of control were confirmed. In addition, a serendipitous finding emerged. This finding was that for certain encoding of the ground plane there was a gradual drift of the internal referent away from the external referent in a manner similar to the drift of an auditory standard. Thus, identifiable forms or objects upon the ground plane were important in order to maintain the required juxtaposition between internal and external referent or simply to maintain the identify of the external referent. If this finding is verified or supported in a more dynamic and complete experimental apparatus such as the Jaycopter, it is important for the encoding of the ground plane particularly for those encodings created by computer graphics. The Jaycopter lends itself to the test of this model and to a test of the dependency of the predictions upon the way in which the ground plane is encoded. Experiments carried out in the test of this model can and should be carried out simultaneously with the ground encoding experiments recommended in Section 7.3.2.

7.3.4 Geometric Description of Visual Space

The Matheny-Thielges model described in Section 7.3.3 is based upon perspective geometry, sometimes called picture plane geometry. This geometry assumes a linear projection of the real world scene upon a two dimensional surface viewed by the pilot. It would appear that Gibson's description of visual space is also dependent upon such geometry.

The work of Luneburg (1947) and the relevant experimental work described by Blank (1959, 1961) would indicate that visual space may best be described as Riemannian with constant Gaussian curvature. The essential problem would appear to be the sign of the curvature (K); whether it is positive (spherical geometry) negative (hyperbolic) or zero (Euclidian). The results of experimental investigations would indicate that at small distances visual space might best be described as Riemannian space with constant Gaussian curvature of negative sign, i.e., it is hyperbolic. That is to say that objects lying on a transverse plane or line would appear to be bowed away from the subject. At medium distances the objects would appear to lie on a transverse straight line and be best described by Euclidian geometry, i.e., Gaussian curvature with zero sign. At greater distances objects lying on a transverse line would appear to be bowed toward the subject, i.e., best described by spherical geometry or Riemannian space with constant Gaussian curvature of positive sign. Such curves have been called Helmholtz geodesics and Luneburg (1947) presents a method of computing the distances at which the curve exhibits no bowing.

Whether the questions raised by Luneburg's theory of visual space are important to the generation of visual displays for ground based trainers may or may not be of practical significance. It is believed and recommended, however, that the full implications of the work on the description of visual space be investigated for its possible importance to visual displays. It may mean simply that the projection surface or the surface on which the visual scene is displayed must be curved, i.e., circular. Until such an examination of the theory and the experimental data can be made no specific experimental design or variables can be detailed.

7.3.5 Experimental Apparatus for Use in Research on Visual Cues

In consideration of all the experimental questions being raised with respect to the presentation of the visual cues which represent the external world, the type of experimental apparatus required is dependent somewhat upon the priorities assigned to the questions. One of those questions upon which we have focused attention is that of the designation of the relevant cues and how they are encoded into a two dimensional representation of the three dimensional world. The question has also been raised about the effect of masking cues, and particular, the training value of requiring the trainee to sort out the relevant cues from overlying perceptions which tend to mask those cues.

In carrying out research on the method of encoding the ground plane it appears mandatory that the encoding be capable of being varied from the strict stylized perspective geometrical form to that approaching what would be characterized as perceptually equivalent to the real world scene with realism cues liberally added. It is necessary that the forms and relationships among forms, planes and surfaces in the visual scene be capable of being specified precisely whether upon a transverse plane or curved surface. The most cost-effective means at this time for varying visual scene content would appear to be a terrain model with T.V. pickup such that the content of the display can be varied systematically and over a wide range. Further, such a system allows for the introduction of color as a variable.

The projection of the scene viewed by the pilot may be upon a flat two dimensional surface or through collimated optics creating a virtual image. Thus, the pros and cons of virtual imagery as a variable in the training situation can be studied.

At present the television system has certain problems with respect to resolution and brightness. Attempts to study the extent of the field of view will be confounded with problems of display illumination and resolution. As discussed in Chapter 2.0 resolution is a confounding variable in that it effects the perceived contrast. It also interacts with color in that color may enhance contrast and, therefore, resolution. In the study of color as a variable, resolution will likely be a confounding problem with the equipment being recommended here in that resolution attained by color television systems **has** not reached that attainable by the black and white systems. Despite the resolution limitations, however, it is felt that such a system, on balance, would offer the greatest flexibility and capability for studying the problem of visual cues at this time.

The expense and effort to obtain a high resolution television system from which may be obtained the maximum illuminance used in connection with a physical terrain model with its flexibility for changing models upon the ground plane would seem to be the most desirable solution to the visual attachment research tool at the present time.

7.4 MOTION CUE EXPERIMENTATION

The fundamental question with respect to the characteristics of a simulator motion platform is twofold. First, it is necessary to determine what its response characteristics should be in order that it provide cues perceptually equivalent to those in the aircraft. Second, the contribution made by the introduction of motion into the training simulator must be determined empirically. The alternative to empirical transfer of training experiments is the assumption discussed in Section 7.1 that degree of transfer is directly a function of the incorporation of perceptual cues.

With regard to the first question, i.e., the perceptual response characteristics of the platform, it must be determined not only what this response capability must be to provide relevant control cues. It must also be determined what capabilities will accommodate those motions which are disruptive to performance or which mask relevant cues.

Consideration must also be given to the value of uncorrelated motion upon simulator acceptance by the pilot with its possible indirect effect upon training and transfer. The determination of that bandwidth of uncorrelated motion which does not interfere with relevant cues and at the same time provides random "breakloose" motion also is important.

7.4.1 Uncorrelated Motion

As pointed out in Section 3.4.1 the introduction of uncorrelated motion into the simulator platform may not be the simple matter it first appears. Such motion must be essentially random so that it provides the pilot with the sensation of not being "glued" to the ground in a simulator. At the same time its frequency bandwidth must be set so that perception of that motion is not falsely interpreted as a relevant control cue.

The discussion given in Chapter 3.0 relative to the resonant and disturbing frequencies for the head and eyes (approximately 5 and 11 Hz respectively) would indicate that these frequencies should be avoided. The frequencies at 2.5 Hz would appear from the literature to be important aids to visual tracking and therefore discriminable as relevant cues. The bandwidth between approximately 3 and 5 Hz and above 12 Hz would then be suggested as the most likely candidate for noncorrelated random motion. This postulation is in need of experimental investigation.

7.4.2 Correlated Motion

Correlated motion is that motion which coincides with some change in the aircraft system of interest to the pilot and which can provide a cue to this change. Normally the motions of the total aircraft system in three dimensional space are those upon which interest is centered. For specifying what platform frequency response is appropriate for these motions a method of describing and measuring the physical characteristics of the motion must be adopted. This has been discussed in Section 3.5.1 and the description of platform characteristics in the frequency domain has been chosen.

The experimental question is what effective (i.e., hardware and software) frequency bandwidth should the motion platform be capable of providing in order to provide the pilot of a closed man-machine system with the relevant cues to movement of the system in space. From the discussion in Chapter 3.0 the bandwidth from 0 through 3 Hz should be investigated for the determination of both the upper and lower break frequency. From the available data the postulations may be made that the upper break point should be about 2.5 Hz. There are much less data to support postulations about the lower break point. Some very tentative data exists (Stapleford, et al., 1969) which suggests that this point could be as high as 2.0 rad/sec.

The 0 Hz condition is, of course, no motion at all and must be seriously considered for certain tasks, systems, and levels of pilot experience. That is to say that the utility of motion is task, pilot and system specific and investigations aimed at contributing to the most cost-effective solution to the simulator motion problem must take this fact into account. The zero motion condition then must be considered as one level of the experimental variable of motion. Its interactive effect with task and pilot experience and response characteristics of the aircraft being controlled may then be determined experimentally and compared with other levels of the motion variable.

8.0 SUMMARY

This report concerns the problems of multi-sensory cueing: specifically the relationships between visual, aural, motion and control movement cues and the dimensions of aircraft control; the establishment of an analytic basis for cue investigation; the suggestion of research topics; and the determination of simulator facility suitability.

Based on pertinent literature, expert judgment, pilot reports, and investigator experience a cue taxonomy was developed which included sets of relevant and non-relevant cues. Relevant cues were sub-divided into primary, secondary, complementary, and conflicting cues while the non-relevant cues were considered as a group which serves to add realism to the situation.

Two analytic bases for postulating cues were defined as the stimulus environment approach and the information array approach. The former attempts to specify the physical energy spectra of the aircraft system available to and sensible by the pilot and from which the cue or cues would be identified. The information array approach hypothesized that information is displayed as an array of cues and the problem is therefore to identify and select the appropriate cue or cues used in control. Both approaches were aimed at identifying and describing the physical, quantifiable parameters which provide stimulus sources for the cues since the ultimate criterion was the application of the cues to the flight trainer.

Implicit in the investigation of cues for control was the hypothesis that there is some learned standard or referent for control and that there is a controllable index which may be adjusted relative to the standard.

Using the information array approach, several hypotheses were developed regarding the visual cues required for aircraft control. One important question involves the relative adequacy of monocular cues for control. It was hypothesized that, if monocular cues could be demonstrated to be adequate then perspective geometry would be suitable as a descriptive method for the identification and quantification of the cues for trainer application. Consequently a series of experiments were recommended to determine the relative efficiency of monocular and binocular cues in a variety of tasks such as the transfer effect going from monocular training to binocular operational tasks.

Other visual problems have proved worthy of hypotheses regarding their role as cues for control. It was proposed that the advantages and disadvantages of color be explored in terms of whether color is a significant cue for control or merely adds realism. An empirical investigation of collimated display systems was also proposed in order to answer such questions as the comparison between a flat plane two dimensional projection versus one using virtual imagery.

The field of view was pointed to as another important area which required empirical investigation. Variables such as the extent of the horizontal visual horizon, the configuration of the ground plane, and the density and shape of the textural elements defining the ground plane are relevant problems.

Postulates as to cues for motion have been presented based upon considerations of the results in the physiological, psychophysical and behavioral sciences literature. Findings in these areas were discussed and experiments have been outlined which are designed to test the validity of the postulates and lead to their verification or modification.

General considerations were outlined and concepts such as "exoskeleton" were introduced in which the pilot is presumed to view the aircraft as an extension of himself. The interrelationships between muscle tension, postural tonus, and the vestibular were developed to form a theoretical framework from which postulates could be derived in terms of motion sensing.

Before training device requirements could be specified, it was pointed out, an analysis of platform motion would be necessary. It was thus proposed that motion be analyzed using frequency analyses in order to specify performance criteria. The description of the system characteristics would then allow for a specification on the system response to any driving function, thus making it possible to vary the system characteristics systematically and then determine the relation of this variation to pilot control behavior.

Kinesthetic cues were operationally defined as cues derived by the operator from the movements of his limbs as he actuates controls. It was pointed out that little has been published regarding the use of kinesthetic cues in control. However, the importance of feedback is generally acknowledged.

Interactive aspects of feedback information were presented and it was proposed that the construct, "the effective time constant", be used to assess the characteristics of the control device by measuring and systematically varying it as the independent variable.

The stimulus environment approach was deemed the more feasible for investigating the problem of auditory cues. Several hypotheses were generated regarding possible aural cue sources for aircraft control but the main contention dealt with accurate information about such sources in terms of amplitude, frequency, and complexity of the wave forms generating the cues. Because the ultimate goal is the presentation of aural cues in the trainer, accurate information about characteristics of the cues is required to verify the postulations that pitch and loudness serve as the auditory cues for control. This was not deemed a simple operation, however, and it was pointed out that other considerations are necessary. As a consequence of the necessity for additional information it was recommended that sound recordings at the operator's station in cockpits of the aircraft of interest be made so that the postulates could be either verified or modified. Special considerations for recording were presented along with a possible data gathering approach.

Hypotheses were presented regarding interactions among cues which have a direct implication for cue application to the trainer. It was pointed out that there are possible interactions between the visual and motion cues in terms of dominance of the cue and the fact that cues can change from primary to complementary to conflicting etc. Further, there may be an interaction between the gain of the visual display and the motion cues. Color of the display was seen as a possible source of interaction with the motion cue derived from the platform motion.

It was also pointed out that there could be an interactive effect between the kinesthetic and motion cues. This would involve particularly the feedback loop. Too, the possibility of interaction between kinesthetic feedback and visual cues was deemed important.

Finally, it was pointed out in this report that the ultimate question to which an answer is sought deals with the relationship between the degree of incorporation of cues into the ground based trainer and the amount of transfer to the actual system.

Several contingencies make the transfer-of-training experiments costly in terms of money, manpower, and training time. Alternatives were suggested.

It was pointed out that the Jaycopter could be utilized as a tool for visual experiments. Such alternatives assume that there is a relationship between the degree of trainer effectiveness and the degree to which relevant cues are incorporated into the trainer. A concomitant variable is the problem of performance measurement since the question to be answered is whether the trainer requires the same responses as does the aircraft.

It was proposed that performance be measured in terms of system output and operator output. System output was defined as the measurement of system parameters directly related to the performance of the pilot and the task performed while by operator performance is meant the spatial and temporal pattern of the control movements which the pilot makes in bringing about the desired system outputs. Procedures for these performance measurements were then outlined, with especial reference to testing visual parameters.

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APPENDIX A

POSTULATED CONTACT VISUAL CUES FOR AIRCRAFT CONTROL

NOTE: Postulated cues listed assume constraints on the size of the visual display to be 60 degrees either side of the midline in azimuth and 30 degrees above and below the level flight horizon line.

POSTULATED CONTACT VISUAL CUES FOR AIRCRAFT CONTROL

DIMENSION OF CONTROL	EXTERNAL REFERENT	INTERNAL REFERENT (OWN A/C)	CUE TO CONTROL	DESCRIPTIVE METHOD	MASKING CUES
1. Pitch (Primary)	Horizon line	Point fixed on aircraft	Alignment or relative position of referents	Perspective geometry	Atmospheric attenuation of external referent e.g., haze, reducing definition or acutance
2. Pitch (Secondary)	Ground plane extension in front of a/c	Point fixed on aircraft	Alignment or relative position of referents	Perspective geometry	A. Atmospheric attenuation B. Lack of definition of ground plane due to lack of textural definition, e.g.,smooth water
3. Pitch rate (Primary)	Horizon line	Point fixed on aircraft	Learned and stored rate of change of relative position of the two referents	Perspective geometry	Attenuation of external referent as in number 1
4. Pitch rate (Secondary)	Ground plane extension in front of a/c	Point fixed on aircraft	Learned and stored rate of change of relative position of the two referents	Perspective geometry	Atmospheric attenuation as in number 2

DIMENSION OF CONTROL	EXTERNAL REFERENT	INTERNAL REFERENT (OWN A/C)	CUE TO CONTROL	DESCRIPTIVE METHOD	MASKING CUES
5. Roll (Primary)	Horizon line	Structure or line fixed on aircraft	Alignment or relative angular position of referents	Perspective geometry	Atmospheric attenuation of external referent as in number 1
6. Roll (Secondary)	Ground plane extension in front of the aircraft	Structure or line fixed on aircraft	Alignment or relative angular position of referents	Perspective geometry	Atmospheric attenuation or lack of definition of ground plane as in number 2
7. Roll rate (Primary)	Horizon line	Structure or line fixed on aircraft	Learned and stored rate of change of the angular positions of the two referents	Perspective geometry	Atmospheric attenuation as in number 1
8. Roll rate (Secondary)	Ground plane extension in front of the aircraft	Structure or line fixed on aircraft	Same as number 7	Perspective geometry	Atmospheric attenuation or lack of definition of ground plane as in number 2
9. Yaw (Primary)	Point virtually on horizon directly aligned with longitudinal axis of a/c	Point fixed on a/c directly in front of pilot, i.e., on line of regard to external referent	Alignment or relative position of referents	Perspective geometry	Atmospheric attenuation as in number 1

DIMENSION OF CONTROL	EXTERNAL REFERENT	INTERNAL REFERENT (OWN A/C)	CUE TO CONTROL	DESCRIPTIVE METHOD	MASKING CUES
10. Yaw (Secondary)	Point on near ground plane and/or displaced in azimuth from aircraft longitudinal axis	Point fixed on aircraft directly in front of pilot or, alternatively, displaced laterally or vertically from line of regard to external referent	Alignment or relative position of referents	Perspective geometry	Atmospheric attenuation or lack of ground plane definition as in number 2
11. Yaw rate (Primary)	Same as 9	Same as 9	Learned and stored rate of change of relative positions of referents	Perspective geometry	Attenuation of external referent as in number 1
12. Yaw rate (Secondary)	Same as 10	Same as 10	Same as 10	Perspective geometry	Atmospheric attenuation or lack of ground plane definition as in number 2
13. Altitude-Hover (Primary)	Forms on ground plane	None	Learned and stored size of identifiable forms on ground plane	Perspective geometry	Atmospheric attenuation or other factors which degrade the resolution or acutance of the form

DIMENSION OF CONTROL	EXTERNAL REFERENT	INTERNAL REFERENT (OWN A/C)	CUE TO CONTROL	DESCRIPTIVE METHOD	MASKING CUES
14. Altitude-Hover (Secondary)	Two points on ground plane lying on pilot's line of regard and separated by discriminable distance	None	Learned and stored separation distance between the two points on the ground plane	Perspective geometry	Atmospheric attenuation or any factor which degrades the resolution of the two points
15. Altitude rate-Hover (Primary)	Forms on ground plane	None	Learned and stored rate of change of size of form	Perspective geometry	Same as number 13
16. Altitude rate-Hover (Secondary)	Two points on ground plane as in 14 above	None	Learned and stored rate of change of separation distance of two points	Perspective geometry	Same as number 14
17. Altitude-Level off (Primary)	Elements or objects on ground plane within 50 ft. of aircraft	None	Learned and stored rate of flow of elements on ground plane	Perspective geometry	Any factor which interferes with resolution of the elements
18. Altitude-Level off (Secondary)	Objects on ground plane at distance greater than 100 ft.	Point on own a/c	Own height relative to height of external referent i.e., relative position of the two referents	Perspective geometry	Attenuation as in number 13

DIMENSION OF CONTROL	EXTERNAL REFERENT	INTERNAL REFERENT (OWN A/C)	CUE TO CONTROL	DESCRIPTIVE METHOD	MASKING CUES
19. Altitude rate-Level off (Primary)	Elements or objects on ground plane as in number 17	None	Learned and stored acceleration and deceleration of flow of elements on ground plane	Perspective geometry	Same as number 17
20. Altitude rate-Level off (Secondary)	Objects on ground plane as in 18 above	Point on own aircraft	Learned and stored rate of change of separation of the two referents	Perspective geometry	Same as number 14
21. Altitude-Low [50-200 ft] (Primary)	Objects on ground plane ahead of a/c, distance a function of a/c speed	Point on own a/c	Learned and stored relative position of the two referents	Perspective geometry	Atmospheric attenuation or any factor which degrades the resolution or acutance of the outline of the top of the objects
22. Altitude rate-Low [50-200 ft] (Primary)	Objects on ground plane as in 21 above	Point on own a/c	Learned and stored rate of change of the relative positions of the two referents	Perspective geometry	Same as number 21
23. Lateral translation-Hover (Primary)	Object or point on ground plane	Point on own a/c	Learned and stored relative position of the two referents	Perspective geometry	Factors which degrade the resolution of the two referents or the acutance of the external referent

	DIMENSION OF CONTROL	EXTERNAL REFERENT	INTERNAL REFERENT (OWN A/C)	CUE TO CONTROL	DESCRIPTIVE METHOD	MASKING CUES
24.	Lateral translation rate-Hover	Object or point on ground plane	Point on own aircraft	Learned and stored rate of change of relative position of referents	Perspective geometry	Factors as in number 23
25.	Lateral translation-All altitudes above hover	Same as number 23	Same as number 23	Same as number 23	Perspective geometry	Same as number 23
26.	Fore and aft translation-Hover	Object or point on ground plane	Point on own aircraft	Learned and stored relative position of the two referents	Perspective geometry	Factors which degrade the resolution of the two referents or the acutance of the external referents
27.	Fore and aft translation rate-Hover	Object or point on ground plane	Point on own aircraft	Learned and stored rate of change of relative position of the two referents	Perspective geometry	Factors as in number 26

NOTE: With the display size assumed, a fixed relative position of the two referents may be maintained with a simultaneous change in altitude and aft translation. (Wilkerson and Matheny, 1961a)

DIMENSION OF CONTROL	EXTERNAL REFERENT	INTERNAL REFERENT (OWN A/C)	CUE TO CONTROL	DESCRIPTIVE METHOD	MASKING CUES
28. Position in X,Z space-Elevation on glideslope (Primary)	Horizon line and intended point of impact	None	Learned and stored separation distance between horizon and point of impact	Perspective geometry	Atmospheric attenuation or other factors which degrade resolution of the two external referents
NOTE: Cf Bell, 1951					
29. Position in X,Z space-Elevation on glideslope (Secondary)	Forms or objects on ground plane	None	Perceived size of forms or objects compared to learned and stored referent	Perspective geometry	Factors which attenuate the acutance of external referents
30. Rate of change of position in X,Z- On glideslope (Primary)	Horizon line and intended point of impact	None	Rate of change of separation between the two external referents compared to stored standard	Perspective geometry	Atmospheric attenuation and other factors as in number 28
31. Rate of change of position in X,Z- On glideslope (Secondary)	Forms or objects on ground plane	None	Rate of change of size of forms or objects compared to learned and stored standard	Perspective geometry	Attenuating factors as in number 29

	DIMENSION OF CONTROL	EXTERNAL REFERENT	INTERNAL REFERENT (OWN A/C)	CUE TO CONTROL	DESCRIPTIVE METHOD	MASKING CUES
32.	Position in X,Y space-Lateral position on approach path	Two points or line on ground plane	Point on own aircraft in forward field of view	Relative angular position of external referent	Perspective geometry	Attenuating factors as in number 29
33.	Rate of change or position in X,Y space-Lateral position in approach path	Same as number 32	Same as number 32	Rate of change of angular position relative to stored standard	Perspective geometry	Attenuating factors as in number 29

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Life Sciences, Inc. 7305 Grapevine Highway Fort Worth, Texas 76118	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

AN INVESTIGATION OF VISUAL, AURAL, MOTION AND CONTROL MOVEMENT CUES

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Technical Report - 27 June 1969 - 27 June 1970

5. AUTHOR(S) (First name, middle initial, last name)

W. G. Matheny, A. L. Lowes, G. Baker and J. A. Bynum

6. REPORT DATE April 1971	7a. TOTAL NO. OF PAGES 105	7b. NO. OF REFS 104
8a. CONTRACT OR GRANT NO. N61339-69-C-0304 b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Report: NAVTRADEVCEN-69-C-0304-1 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES Technical Report as a part of an ongoing project	12. SPONSORING MILITARY ACTIVITY Naval Training Device Center Orlando, Florida

13. ABSTRACT

This report is devoted to the determination of how multi-sensory cues can be simulated and effectively used in the training of pilots. An analytical basis and cue taxonomy is developed and cues are postulated on the basis of information gained from the outside visual world, from sounds generated by the aircraft, and from cues resulting from aircraft motion and control movements. Description and measurement of the physical characteristics of the postulated cues are emphasized. Hypotheses are developed based upon the effects of postulated cues as they both function independently and interact with cues in other modalities. Experimentation is recommended which will lead to verification or modification of cue postulations.

DD FORM 1 NOV 65 **1473**

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Multi-sensory cueing						
Simulator						
Visual Cues						
Motion Cues						
Aural Cues						
Piloting Training						